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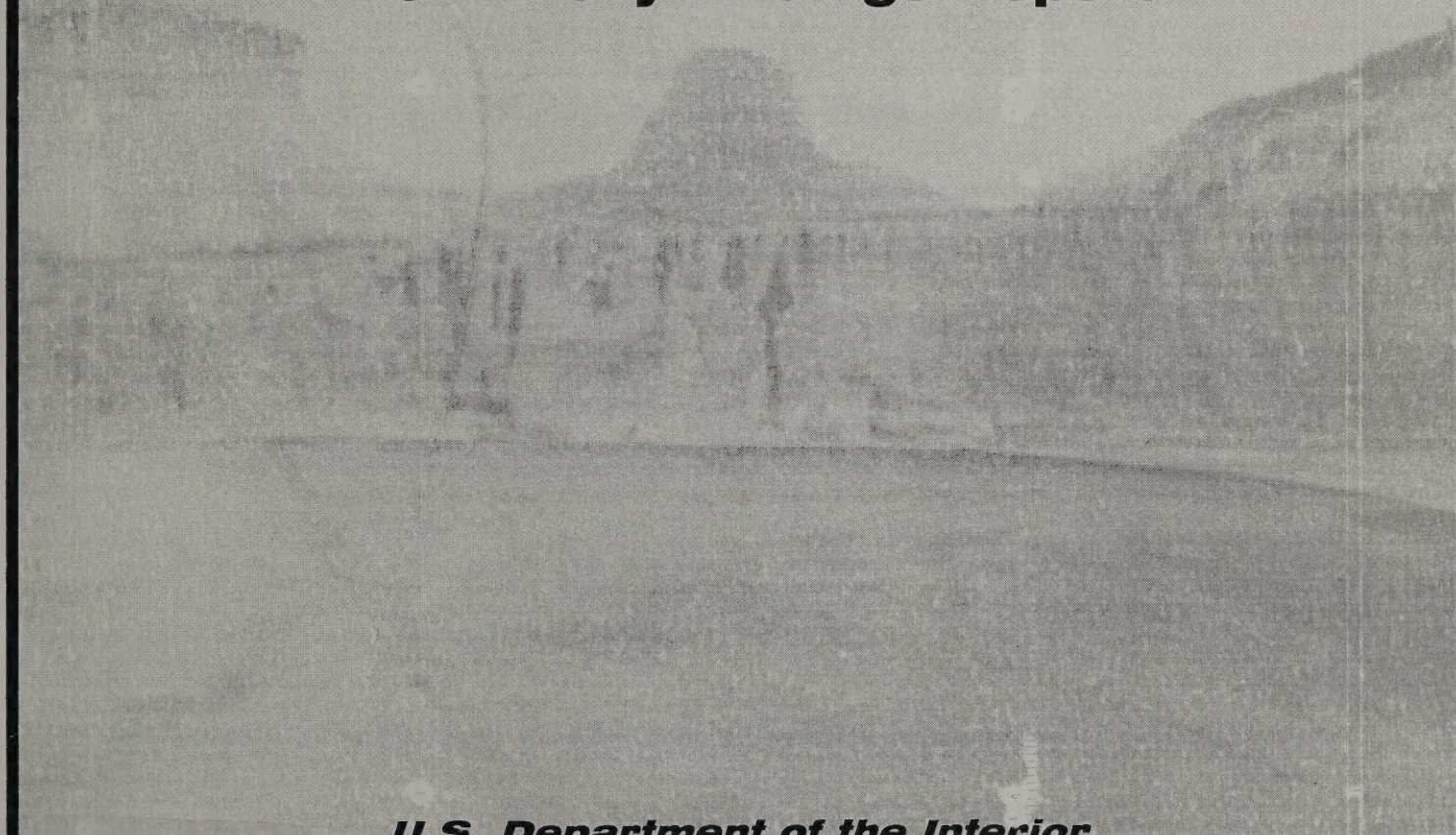
RIO PUERCO SEDIMENTATION AND WATER QUALITY STUDY

Preliminary Findings Report



U.S. Department of the Interior
Bureau of Reclamation
Albuquerque Area Office

October 1996

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U.S. Department of the Interior
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The Mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American Public.

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This report was prepared pursuant to the Act of June 17, 1902. Publication of the findings and recommendations herein should not be construed as representing either the approval or disapproval of the Secretary of the Interior.

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KEY FINDINGS

The sediment load of the Rio Puerco is significantly lower now than it has been in the past. This trend is also evident in other basins in New Mexico.

The rate of sediment deposition in Elephant Butte Reservoir is significantly reduced compared to the rates experienced during early years of reservoir operation.

Reduced sedimentation may be due to climatic change, geomorphic processes, better land management, or structural improvements.

The surface area of Elephant Butte Reservoir, for a given volume in storage, has not increased greatly in the 80 years of reservoir operation to date. This increase has been less than 10 percent. A large increase in reservoir evaporation losses due to sediment deposition increasing the surface area for a given volume of storage is not anticipated in the next 100 years.

Over the next 100 years, the overall effect on the water supply below Elephant Butte Dam due to increasing probability and magnitude of reservoir spills will be small.

At the present time, water supply benefits below Elephant Butte Reservoir cannot justify a major sediment control project on the Rio Puerco.

Sediment deposition at and above Elephant Butte Reservoir will continue to cause channel maintenance problems. However, a sediment control project on the Rio Puerco would probably not provide a cost effective means of reducing channel maintenance.

Radionuclides and heavy metals are discharged to the Rio Grande by the Rio Puerco. Data and research on the quantities of these substances and the mechanisms of transport and storage are limited and inconclusive. The majority of these substances are known to be transported attached to sediment particles rather than being dissolved in the water.

Sampling that has been done to date is not adequate to determine whether there is a threat to humans or the ecosystem along the Rio Grande due to radionuclides or heavy metals from the Rio Puerco.

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INTRODUCTION

Aggradation of the Rio Grande and sedimentation of Elephant Butte Reservoir have been of concern to water users and managers for many decades. The Rio Puerco is an important source of Rio Grande sediments and means of controlling the Rio Puerco's sediment contribution to the Rio Grande have been the subject of considerable study and investigation. In 1928, the Middle Rio Grande Conservancy District recognized the problem in its Official Plan [Burkholder, 1928]. The District had commissioned Kirk Bryan [Bryan and Post, 1927] to do extensive studies of the Rio Puerco and to develop a sediment control plan. Then in 1941, the U.S. Department of Agriculture [1941] issued a final report on a thorough investigation of the Rio Puerco basin and proposed a comprehensive plan for sediment control. Most recently, the U.S. Army Corps of Engineers [1985] studied a plan to construct major dams on the Rio Puerco and Rio Salado[1] for flood and sediment control. None of these plans have been implemented though some local projects have been undertaken, notably by the Bureau of Land Management.

More recently there has been concern that the Rio Puerco may be discharging trace heavy metals and radionuclides into the Rio Grande. Extensive mining and milling of uranium in the Grants mineral belt and associated wastewater discharges prompted increased concern that the Rio Puerco might have adverse water quality effects on the Rio Grande in addition to the long-recognized sediment problem.

In response to these continuing concerns the Bureau of Reclamation (Reclamation) undertook a preliminary reconnaissance study under its General Investigations Program to determine whether adverse impacts on the Rio Grande and Elephant Butte Reservoir could justify development of a sediment control project on the Rio Puerco, and to determine whether the Rio Puerco is transporting trace metals and radionuclides into the Rio Grande in quantities that might pose risks to humans or ecosystems downstream. The findings of this preliminary reconnaissance investigation are detailed in the following report.

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[1] The Rio Salado referred to in this report is that Rio Salado which flows into the Rio Grande from the west between Bernardo and San Acacia. Another Rio Salado adjacent to the Rio Puerco is a tributary of the Jemez River.

Reduction of the sediment load in the Rio Grande below the mouth of the Rio Puerco would address the following previously identified needs:

1. Reduction of water losses due to sediment deposition in Elephant Butte Reservoir,

2. Reduction of Rio Grande channel maintenance costs,

3. Enhancement of water conveyance efficiency in the Rio Grande between the Rio Puerco and Elephant Butte Reservoir,

4. Miscellaneous benefits of enhanced flood control and protection of infrastructure facilities,

5. Preservation and enhancement of recreational values,

Potential for radionuclides and trace metals to affect the population and ecosystem of the Rio Grande Valley below the confluence of the Rio Puerco is largely unknown. It is a purpose of this reconnaissance investigation to review the current knowledge of this subject for adequacy in determining these risks.

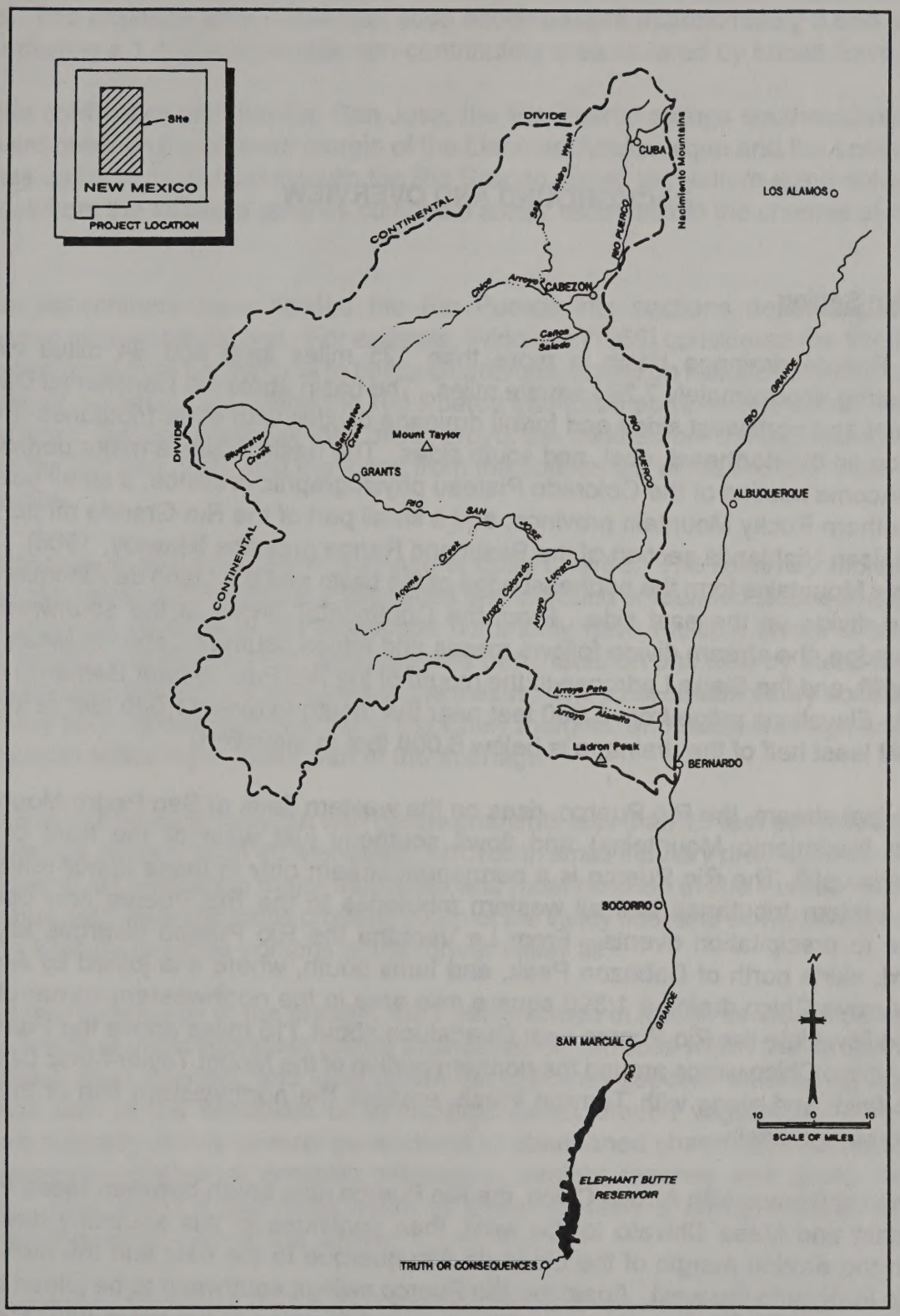

Figure 1: Map of the Rio Puerco Basin

BACKGROUND AND OVERVIEW

Geographic Setting

The Rio Puerco drainage basin is more than 125 miles long and 94 miles wide, encompassing approximately 7,294 square miles. The basin abuts the Continental Divide on the west and northwest sides and forms drainage divides with other tributaries of the Rio Grande on the northeast, east, and south sides. The basin drains a major portion of the Zuni-Acoma section of the Colorado Plateau physiographic province, a small portion of the Southern Rocky Mountain province, and a small part of the Rio Grande rift portion of the Mexican Highlands section of the Basin and Range province [Hawley, 1986]. The Nacimiento Mountains form the northeast edge of the basin and the Llano de Albuquerque forms the divide on the east side. From the Continental Divide at the southwestern drainage edge, the stream divide follows mesas and ridges south of Cebollita Mesa, the Lucero uplift, and the Sierra Ladrones to the mouth of the Rio Puerco near Bernardo (see Figure 1). Elevations range from 5,000 feet near the mouth to over 11,000 feet at Mount Taylor. At least half of the drainage is below 6,000 feet in elevation.

The principal stream, the Rio Puerco, rises on the western flank of San Pedro Mountain (northern Nacimiento Mountains) and flows southerly just west of the front of the Nacimiento uplift. The Rio Puerco is a permanent stream only in these upper reaches. Smaller eastern tributaries and all western tributaries to the Rio Puerco flow only in response to precipitation events. From La Ventana the Rio Puerco diverges slightly westward, skirts north of Cabezon Peak, and turns south, where it is joined by Arroyo Chico. Arroyo Chico drains a 1,390 square mile area in the northwestern corner of the basin and flows into the Rio Puerco near Guadalupe about 115 miles above the Puerco's mouth. Arroyo Chico wraps around the northern portion of the Mount Taylor-Mesa Chivato volcanic field, and along with Torreon Wash, empties the northwestern fifth of the Rio Puerco drainage basin.

Below the confluence with Arroyo Chico, the Rio Puerco runs south between Mesa Prieta to the east and Mesa Chivato to the west, then continues in this southerly direction between the eroded margin of the Llano de Albuquerque to the east and the mesas of Colorado Plateau to the west. Again the Rio Puerco swings southwest to be joined by its primary tributary, the Rio San Jose near Correo, about 45 miles above the mouth. The Rio San Jose is formed from streams which rise in the Zuni Mountains, the southern portion

of the Mount Taylor volcanic field, Cebolleta Mesa, and the northwestern flank of the Sierra Lucero. The drainage area of the San Jose encompasses approximately 3,660 square miles including a 1,130 square mile non-contributing area covered by basalt flows.

From the confluence with the Rio San Jose, the Rio Puerco swings southeastward and southward between the western margin of the Llano de Albuquerque and the Lucero and Ladrones uplifts to its confluence with the Rio Grande. Small to medium-sized ephemeral drainages from the adjacent uplands contribute sandy sediments to the channel along the way.

Different researchers have divided the Rio Puerco into sections depending on the purposes of their investigations. For example, Widdison [1959] considered the Middle Rio Puerco to extend from La Ventana to below Guadalupe, based on historic settlements. For purposes of this study, we divide the Rio Puerco into three portions, the upper from the headwaters to the confluence of the Chico Arroyo, the middle from the confluence of the Chico to the Rio San Jose, and the lower from the confluence of the Rio San Jose to the Rio Grande.

The landscape in the Rio Puerco drainage is quite diverse. The relatively moist, cool, forested mountains commonly have landslides and subdued or rounded slopes and ridges. Lower semi-arid portions of the landscape commonly have multiple levels of tributary valleys, mesas and cuestas (i.e. sloping plains terminated on one side by steep slopes). Old, inactive landslides mark the flanks of the mesas. The axial stream valley contains the main valley floor, stream terraces along the valley margins, and mass-wastage and cliffs along canyon sides in the upper part of the drainage.

Valley floors are typically fairly flat with gentle gradients less than 15 feet per mile and are entrenched by arroyos 10 to 40 feet deep. Arroyos in small tributary drainages tend to be fairly straight; arroyos along major tributaries and most reaches of Rio Puerco mainstem are sinuous, with meander loops crossing much of the valley floor and slowly sweeping and swinging laterally to erode portions of the former valley fill.

Detailed geomorphology of the present Rio Puerco arroyo in many reaches includes one or more levels of inner floodplain (some abandoned as terraces within the arroyo cut), a meandering inner channel, and local eolian (wind borne) deposits stacked against the downwind side of the floodplain or as coppice dunes around vegetation. The inner floodplain typically shows several generations of abandoned channels or oxbows. The active channel consists of complex meanders, straight reaches and gently arcuate reaches. One reach a few miles south of Cuba contains a sandy braided channel occupying the entire width of the arroyo.

In many reaches, tamarisks (salt cedar) are the dominant vegetation along the margins of the inner channel, and are a factor affecting the geometry of the inner channel. Willows

and cottonwood trees occur locally. Most vegetation becomes more sparse away from the inner channel.

The Rio Puerco basin is, in general, sparsely populated. Grants New Mexico, on the Rio San Jose is the biggest town in the basin with a population of 8,000. Cuba NM (Pop. 800) is the principal town and trading center in the upper Rio Puerco basin. Stock raising, trade, and government are the main employment in the area.

Land ownership in the basin is diverse. Approximately 25 percent of the basin is Indian land. Indian reservations contained all or in part in the Rio Puerco Basin are Acoma Pueblo, Laguna Pueblo, Canoncito Navajo, Isleta Pueblo, Zia Pueblo, Jemez Pueblo, Ramah Navajo, and Jicarilla Apache. In addition to the Indian lands, about 40 percent of the basin is privately owned, 25 percent of the land is Bureau of Land Management and National Forest land, and about 10 percent is state land or is owned by miscellaneous federal agencies.

The Rio Puerco directly or indirectly affects a segment of the Rio Grande valley extending from the confluence near Bernardo, New Mexico south to Fort Quitman, Texas. The Rio Grande valley is heavily populated and intensively cultivated. Metropolitan area encompassing El Paso, Texas and Ciudad Juarez, Chihuahua is the largest community in this section of the valley. Las Cruces, New Mexico is the second largest city in New Mexico. Other important communities are Socorro NM, Truth or Consequences NM, and Hatch NM. The Tri-City regional area encompassing El Paso, Juarez, and Las Cruces is expected to have a population of 3.5 million by the year 2010. Below El Paso, the Rio Grande forms the international border between the United States and Mexico.

The Rio Grande supplies water for irrigation of about 19,000 acres between Bernardo and Elephant Butte Reservoir. The Middle Rio Grande Conservancy District operates and maintains the irrigation system in the area down to the northern boundary of the Bosque del Apache National Wild Life Refuge. Principal crops are alfalfa and irrigated pasture.

Elephant Butte Reservoir supplies water for irrigation of approximately 150,000 acres in the Rio Grande Project. Principal crops include alfalfa, cotton, chile peppers, and pecans. The total crop value for lands in the Rio Grande Project area in 1990 was $180,000,000. In addition, the Rio Grande Project supplied approximately 9 billion gallons (27,000 acre feet) of water for municipal and industrial purposes. [Bureau of Reclamation, 1990b] Municipal and industrial water uses are expected to become increasingly important in the future. Under international treaty obligation, 60,000 acre feet of water per year is supplied from Elephant Butte Reservoir to Mexico at the heading of the Acequia Madre near the International Dam at El Paso. The Elephant Butte Irrigation District (EBID), El Paso County Water Improvement District No.1, and the Hudspeth County Conservation District operate and maintain irrigation delivery systems below Elephant Butte Dam.

Elephant Butte Reservoir is an important recreational resource, providing boating, fishing, and swimming opportunities. Elephant Butte State Park averages about 1,500,000 visitor days annually.

The Bureau of Reclamation constructs, operates, and maintains channels above Elephant Butte Reservoir to promote efficient drainage and water conveyance. These works include the Low Flow Conveyance Channel and the Rio Grande Floodway. The Low Flow Conveyance Channel is a man-made channel designed to convey up to 2,000 cubic feet per second of water between San Acacia NM and Elephant Butte Reservoir with a minimum of infiltration and evapotranspiration losses. The Rio Grande Floodway is the natural river channel stabilized and maintained to promote efficient delivery of water to the reservoir. Management of the heavy sediment load of the Rio Grande above Elephant Butte Reservoir is an essential maintenance requirement requiring substantial continuing effort. Reclamation also maintains the Rio Grande channel between Elephant Butte Dam and Caballo Reservoir and between Caballo Reservoir and Percha Diversion Dam. The International Boundary Water Commission maintains the river channel below Percha Dam.

The Rio Grande, its associated riparian areas, adjacent wetlands, and Elephant Butte Reservoir are important habitat areas for a diverse fish and wildlife community. The Bosque del Apache National Wildlife Refuge provides important wintering area for migratory waterfowl as well as habitat for many other species. Crops raised on the refuge are an important source of wildlife forage. The La Joya Game Refuge is owned and operated by the New Mexico Department of Game and Fish and is primarily managed as habitat for waterfowl. The Sevilletta National Wildlife Refuge borders on the Rio Grande and is reserved as an area of minimum human influence.

Bedrock Geology of the Rio Puerco Basin

The geology of the Rio Puerco drainage basin is an important factor influencing erosion and sediment yield. The basin is underlain by a variety of rocks and less-consolidated deposits. Figure 2 shows the distribution of rocks of different ages in the drainage basin; Appendix C contains an outline of the geologic history as it relates to erosion, sediment transport, deposition, and sediment quality; and Table 1 shows relative proportions of rocks and deposits in the basin determined by identifying geologic units beneath intersections of 212 township and range lines on the 1:500,000 scale geologic map of New Mexico [Dane and Bachman, 1965]. More than 80 percent of the basin is developed in easily erodible mudstone, shale, and sandy sediments.

As shown in Table 1, over 40 percent the drainage basin is underlain by Cretaceous sandstones, shales, and coals. Another 7 percent is underlain by similar Lower and Middle Tertiary sediments. These rocks are soft, easily erodible, and are major contributors of fine sands, silt and smectitic clays within the drainage basin. They crop out across the western

two-thirds of the drainage and underlie most of the younger lava flows. The Cretaceous and Lower Tertiary sediments overwhelmingly dominate the upper Rio Puerco, Torreon, and Chico drainage and furnish much of the tributary sediment in the middle reach of the Rio Puerco. Sediment derived from Cretaceous outcrops also dominates tributaries of the North Plains and Lower Rio San Jose and northern tributaries of the upper Rio San Jose. Cretaceous coals and other organic-rich rocks (humates, dark shales) are known to have elevated amounts of heavy metals and sulfur. No studies have been done to show how these elevated amounts of metals are diluted downstream from their outcrops.

Table 1: Percentages of geologic units exposed in the Rio Puerco drainage basin [from Popp and others, 1988]

UNIT	PERCENTAGE
Thick Late Quaternary sediments (mostly Holocene fill)	9.4
Upper Tertiary and Lower Quaternary basin fill	6.1
Upper Tertiary and Quaternary volcanic rocks	17.0
Lower and Middle Tertiary sediments and volcaniclastics	6.6
Cretaceous sandstones, shale, and mudstones (minor coal)	40.6
Jurassic sandstone, mudstone, limestone, and gypsum	4.7
Triassic mudstone and sandstone	5.7
Upper Paleozoic limestone, mudstone and sandstone	7.5
Precambrian igneous and metamorphic rocks	2.4
Total	100

Nearly 18 percent of the basin is underlain by upper Paleozoic to Jurassic sandstone, limestone and shale. Of these formations, the Chinle and Abo (combined 6 percent) are major contributors of red clays to the basin fill and modern sediments. Rocks of Jurassic age produce most of the uranium for which the region is known. Most of the uranium ore deposits were formed by downward movement of uranium-bearing waters flowing through sandstone and depositing uranium as water chemistry changed at depth. Most of the uranium occurring in surface rocks has been leached away and the ore deposits occur at some depth. Waste rock from mines and mill tailings at the surface are primary sources of radionuclides and heavy metal contaminants in local drainages.

About 15 percent of the drainage area is covered by late Tertiary and Quaternary basin fill. The majority of this basin fill occurs along the lower reaches of the drainage. These

Because long-term weather records in the Rio Puerco basin are lacking, records from nearby stations such as Santa Fe and Albuquerque must be used to look for trends. Leopold [1951] and Leopold and others [1966] noted that the mean annual precipitation at Santa Fe had not changed between the first and second half-century's records, but the frequency of daily rainfall amounts had changed. Both the summer and non-summer rains of less than 0.5 inches decrease between the 1930's and 1950's (with some exceptions) and the number of larger rains slightly increase, indicating higher rainfall intensities. A similar episode of higher intensity precipitation took place in Santa Fe from the 1850's to 1880. Leopold suggested that smaller rains favor increased vegetation growth and reduce runoff, whereas larger, intense rains produce more runoff and erosion.

Other workers [Martin, 1963; Schoenwetter and Eddy, 1964; Tuan, 1966] suggested that winter precipitation is less intense than summer rain, so that shifts from winter-dominant to summer-dominant moisture may bring about more runoff and increased erosion. Some authors went further to suggest that summer precipitation caused arroyo entrenchment while winter precipitation caused arroyo infilling. However, precipitation and stream flow records do not support these conjectures.

Temperatures also depend on location in the drainage basin, with the range from maxima over 100 degrees (F) to minima less than -40 degrees (F). The area has warm summers and cold winters, with large diurnal temperature ranges (>40° F). Average growing season (frost-free days) ranges from more than 180 days near the mouth of the Rio Puerco to around 120 days in Cuba and Grants to less than 60 days in the mountains. Free water evaporation ranges from more than 60 inches in lowlands to less than 40 inches in the mountains.

D'Arrigo and Jacoby [1991] used tree-ring indices for two species of pines in the Northwest Plateaus section of New Mexico to extend the cool-season precipitation chronology from AD 985 to 1970 . These authors demonstrated that wetter cool-season conditions in northwestern New Mexico correspond with warmer events during El Nino-Southern Oscillation (ENSO) years. The interpreted worst five droughts in order of descending severity are AD 1577-1598, 1955-1964, 1895-1904, 1217-1226, and 1778-1787. The periods with the most precipitation are AD 1835-1849, 1905-1928, 1429-1440, 1601-1623, and 1487-1498. Extreme moisture in 1816, an ENSO year, also may have been affected by the eruption of the Mount Tambora volcano in 1815. The extremely dry period from 1895 to 1904 was followed by the extremely wet period from 1905-1928. According to D'Arrigo and Jacoby, this is the most abrupt shift from severe drought to sustained precipitation in the past 1,000 years. In an earlier study, Stockton and Jacoby [1976] showed that in the Upper Colorado River Basin the interval of 1906-1930 was the most persistent high-runoff period in the past 450 years and that in the San Juan River basin adjacent to the Rio Puerco the period from 1907 to 1932 was the greatest high-flow period in the past 360 years. Molles and Dahm [1990] also showed a correlation between El Nino years and high spring flows in the Pecos and Gila Rivers.

Ely et al. [1993] studied flood deposits and made high-water estimates for 19 river basins in Arizona and Utah. The deposits found in slackwater areas in bedrock canyons show evidence of 251 floods which appear to have occurred in distinct time intervals. The earliest flood deposits were roughly 5,000 years old. Modern floods on these rivers appear to correlate with cool, moist weather and frequent El Nino events. Modern floods are due to winter North-Pacific-frontal storms, late summer and fall storms from Pacific tropical cyclones, and local summer convective thunderstorms. Past floods on these rivers were most frequent from 4,800 to 3,600 years before present (BP), around 1,000 years BP, and after 500 years BP. No floods were recorded between 3,600 and 2,200 BP or between 800 and 600 years BP.

Hydrology

The Rio Puerco is an ephemeral stream in all but its highest reaches. The river flows mainly during the summer and fall when intense thunderstorms frequently occur over the basin. Approximately 90 percent of the Rio Puerco's flow at the mouth near Bernardo occurs during the months of May through October. The average annual discharge of the Rio Puerco near Bernardo for the period of record (1939 - present) is 32,000 acre feet. This is about 4 percent of the mean annual flow of the Rio Grande at San Acacia about 10 miles below the Rio Puerco confluence. The Rio San Jose discharges an average of approximately 8,000 acre feet per year to the Rio Puerco below Correo. Average flow of Arroyo Chico is about 15,000 acre feet per year.

Runoff from the Rio Puerco is much lower than for the Rio Grande basin as a whole. Relative to drained area, the Rio Puerco yields only 3.7 acre feet of water per square mile per year compared to 37 acre feet per square mile per year for the entire basin above San Marcial. This discrepancy is actually much greater considering the large quantities of water depleted from the Rio Grande for irrigation.

Extreme floods are of considerable interest in the hydrology of the Rio Puerco. Two large floods in 1929 are especially significant. These floods, occurring simultaneously on the Rio Puerco and Rio Salado, caused much damage in the Rio Grande valley. Sediment deposited by the flood waters on crop lands and in the town of San Marcial was particularly destructive. The town of San Marcial was essentially abandoned as a result of the damage caused by these floods.

Floods on the Rio Puerco are poorly documented before the 20th century. Failure of small dams is documented as early as 1877 [Bryan, 1928]. Lopez [1982] documented the failure of the "Old English" Dam and other irrigation structures in 1896. The Old English Dam was a fairly large masonry dam on the Rio Puerco about 30 miles below San Luis that was constructed by the Rio Puerco Irrigation Company. The failure of the abutment of this dam drained a lake two miles long. Ruins of the Old English Dam still survive. A dam on the

Arroyo del Cuervo apparently failed at the same time, adding to the flood. No study has documented the downstream effects of these floods. Smaller diversion dams continued to be built and to fail in the Guadalupe-Cabezon-San Luis reaches of the Rio Puerco until 1951 [Widdison, 1959].

Heath [1983] reviewed gaged floods on the Rio Puerco. At Rio Puerco Station near the railroad bridge 16 miles west of Los Lunas, a flood in 1909 reached a stage height of 9.9 feet, but no discharge estimate was calculated. In 1922, a concrete weir/drop structure was built at this site to help gage the flow more accurately.

The first of the big floods of 1929 occurred on August 12 after heavy rain across the entire upper basin on the previous two days, the gage at Rio Puerco recorded a depth of 16.02 feet and discharge was calculated at 31,509 cubic feet per second (cfs). At Bernardo, discharge was calculated to be 30,643 cfs. Then, on September 23, 1929, after three days of widespread heavy rains, the gage at Rio Puerco peaked at 18 feet, with a calculated discharge of 37,700 cfs. At Bernardo, maximum discharge was calculated to be 35,000 cfs. The flood took out both the highway and railroad bridges at Rio Puerco and destroyed the stream gage.

Lesser floods are documented at the Rio Puerco gage in 1935, 1936, 1941 and 1972 with discharges of 28,000, 27,400, 16,900, and 22,200 cfs respectively [Heath, 1983]. The 1972 flood came primarily from Arroyo Chico.

Floods tend to attenuate between the Rio Puerco and Bernardo gages. Peak gage heights are generally lower at Bernardo and floods take a longer time to pass, so the volume passing the two gages remains nearly the same. During the period from 1940 to 1976, records show that short-term discharge peaks were reduced an average of 24 percent between the gages. However, when tributaries of the lower Rio Puerco flow at the same time as the flood peak, as occurred in 1941, discharge increases downstream to Bernardo.

According to Heath [1983], the lower Rio Puerco generally loses water as it flows downstream to subsurface infiltration and evapotranspiration. Between Rio Puerco gage and Bernardo gage, an average of about 1.7 million cubic feet per mile per year is lost by infiltration [Heath, 1983]. The distance from Rio Puerco to Bernardo is about 40 miles, so these losses would amount to about 1,500 acre feet per year. During the winter months, flows up to 5 cfs at Rio Puerco gage do not reach Bernardo. During summer months, flows as much as 10 cfs at the Rio Puerco gage do not reach Bernardo. This loss of water may tend to increase the river's sediment concentration.

EXISTING CONDITIONS, IMPACTS, AND TRENDS

Erosion and Sediment Yield of the Rio Puerco

The sediment load of the Rio Puerco is high because of the semi-arid climate, land use history, extreme variability in precipitation and streamflow, and the geology and soils of the basin. That it was named "Muddy River" in Spanish colonial times indicates that even before the increased human influences brought by European and American settlement the Rio Puerco was a turbid and muddy stream.

Suspended sediment concentrations in the Rio Puerco are particularly high. Based on U.S. Geological Survey records for the years 1976 through 1992 that were compiled by Resource Technology, Inc. for a recent Corps of Engineers study [Resource Technology Inc., 1994], the average suspended sediment concentration of the Rio Puerco at Bernardo is approximately 107 tons per acre foot or 79,000 milligrams per liter. By comparison the average suspended sediment concentration in the Rio Grande at Bernardo, just above the confluence with the Rio Puerco, is around 0.78 tons per acre foot. In extreme events suspended sediment concentrations as high as 680,000 milligrams per liter have been measured in the Rio Puerco [Bondurant as reported in Nordin, 1963]. Hawley et al. [1983] report that suspended sediment concentrations of 400,000 milligrams per liter are not uncommon. The New Mexico Environment Department has designated the Rio Puerco as an "impaired watershed" largely based on turbidity of the river and on the poor condition of the stream banks and riparian areas.

Annually, the Rio Puerco at Bernardo discharges approximately 2.5 million tons of suspended sediment into the Rio Grande. Total sediment loads (i.e. suspended load plus bed load) are not measured on the Rio Puerco, but based on comparison of total sediment loads on the Rio Grande above and below the confluence a reasonable estimate of the total load of the Rio Puerco can be made. On this basis the total sediment load of the Rio Puerco is estimated to average about 2.75 million tons per year.

The high proportion of suspended sediment relative to total sediment in the Rio Puerco is related to the prevalence of fine materials in the sediment load. Simons and Li [1981] estimated that the sediment load of the Rio Puerco is 90 percent silt and clay size particles (less than 0.062 mm particle diameter) and 10 percent sand. The sediment load of the Rio Grande at San Marcial is approximately 50 percent silt and clay and 50 percent sand [Bureau of Reclamation, 1990].

Bureau of Reclamation [1987] data relating sediment yield to drainage area for 28 reservoirs in semi-arid regions of the United States are shown in Figure 3. According to this analysis an average basin the size of the Rio Puerco's yields 0.23 acre feet, or about 316 tons, of sediment per square mile per year. Actual Rio Puerco sediment yield, at the current rate, is 0.32 acre feet per square mile per year, about 30 percent higher than the average basin.

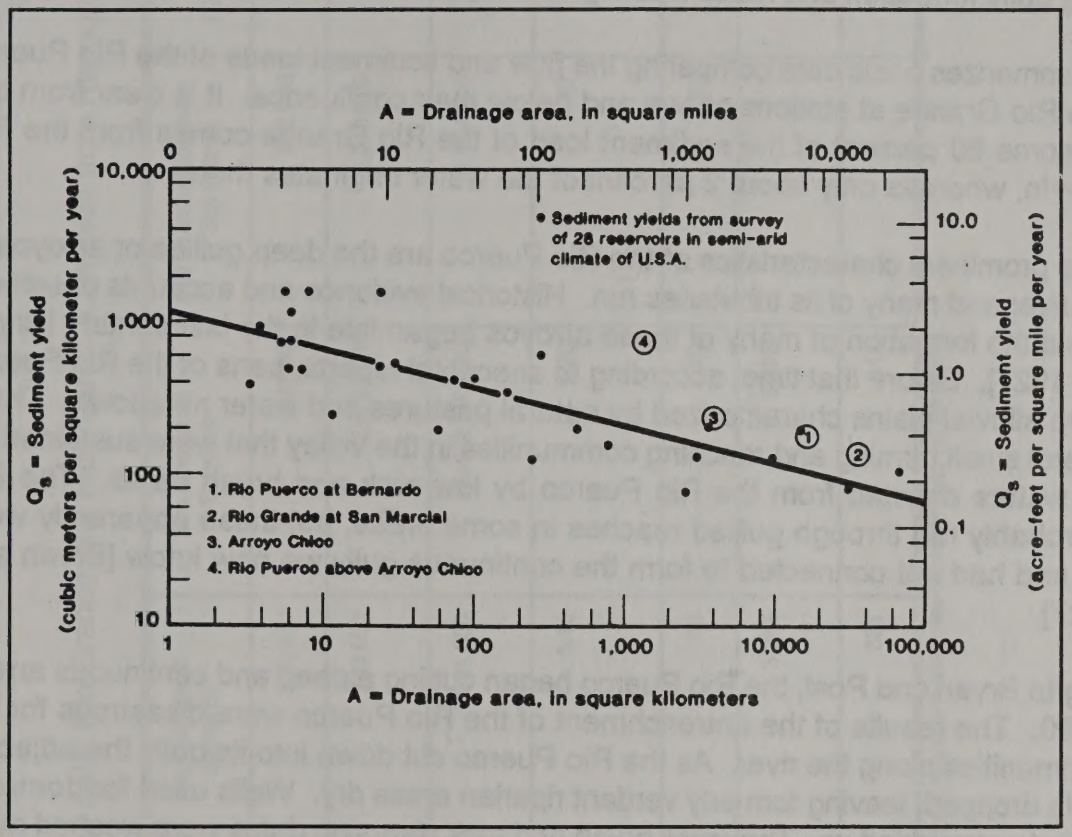

Figure 3: Average Annual Sediment Yield Rate Versus Drainage Basin Area. [Bureau of Reclamation, 1987 (103-D-1806)]

Based on the limited data available, sediment yields of two sub-basins can also be compared to average yields. Sediment records are available for brief periods of record for stations on the Arroyo Chico (1979-1986) and the Rio Puerco above the Arroyo Chico confluence (1982-1992). The sediment yield of the Arroyo Chico is more than double the average value. Sediment yield of the Rio Puerco above the confluence of the Arroyo Chico is about three times the average value. This evidence suggests that these sub-basins may contribute a disproportionate share of the total Rio Puerco sediment yield.

Knowledge of the sources of sediment and the routing of sediment through the system from source to the mouth of the Rio Puerco is very limited. Significant sources of sediment can be identified but there are no recent estimates of their relative contributions to the

overall sediment yield. Happ [1948] cites preliminary estimates by the Department of Agriculture which attribute 40 percent of the sediment load to enlargement of the Rio Puerco channel, 30 percent to enlargement and headward extension of tributary channels, and 30 percent to sheet, rill, and minor gully erosion. Piping of dispersable soils high in exchangeable sodium is also believed to be a significant source of sediment and is a factor in initiating gully formation and mass wasting of arroyo walls.

Table 2 summarizes basic data comparing the flow and sediment loads of the Rio Puerco and of the Rio Grande at stations above and below their confluence. It is clear from the data that some 60 percent of the sediment load of the Rio Grande comes from the Rio Puerco basin, whereas only about 2 percent of the water originates there.

Among the prominent characteristics of the Rio Puerco are the deep gullies or arroyos in which the river and many of its tributaries run. Historical evidence and accounts of settlers indicate that the formation of many of these arroyos began late in the last century [Bryan and Post, 1927]. Before that time, according to anecdotal reports, parts of the Rio Puerco valley were alluvial plains characterized by natural pastures and water meadows. There were several small farming and ranching communities in the valley that were sustained by irrigation waters diverted from the Rio Puerco by low rock and brush dams. The Rio Puerco probably ran through gullied reaches in some areas, but these apparently were localized and had not connected to form the continuous gully we now know [Bryan and Post, 1927].

According to Bryan and Post, the Rio Puerco began cutting a deep and continuous arroyo about 1880. The results of the entrenchment of the Rio Puerco were disastrous for the small communities along the river. As the Rio Puerco cut down into its gully the adjacent water table dropped, leaving formerly verdant riparian areas dry. Wells used for domestic and livestock water dried up. The small brush and rock diversion dams were washed away and the size and height of structures needed to raise water to the levels of the acequia headings increased. Maintenance of diversion structures and irrigation systems became impossible within the available community resources. Farm fields were swallowed by the ever growing gully. One by one the small villages of the Rio Puerco were abandoned. Today the arroyo of the Rio Puerco is hundreds of feet wide and may be 40 or more feet deep where once a small stream flowed on a wide plain. Bryan and Post estimated that 395,000 acre feet of sediment had been moved out of the Rio Puerco basin between 1885 and 1927.

The modern arroyo in the Rio Puerco valley exhibits a complex geomorphic history which has not been fully reconciled with historic accounts of channel widths and depths, land and stream use, and arroyo entrenchment. The upper and lower Rio Puerco show inset terraces which indicate that an arroyo cut and partially filled in before the present arroyo developed. The middle Rio Puerco, however, apparently lacks this episode along its present course. The Albuquerque 15-minute quadrangle, mapped in 1888 and published

Table 2. Summary of sediment and streamflow data, Rio Grande and Rio Puerco, [Compiled from Resource Technology Inc. 1994, and other sources]

	Rio Grande at Albuquerque	Rio Grande at Bernardo	Rio Puerco nr. Bernardo	Rio Grande Floodway at San Acacia	Rio Grande (Combined) at San Marcial
Average annual flow, Acre Feet (1976-1992)	1,058,000	936,000	23,000	792,000	964,000
Suspended Sediment Load, Tons per Year (1976-1992)	819,000	730,000	2,479,000	3,349,000	3,868,000
Total Sediment Load, Tons per Year (1976-1992)	1,197,000	1,081,000	(est) 2,750,000	3,854,000	4,414,000
Total Sediment Load Concentration, Tons per Acre Foot (1976-1992)	1.13	1.15	120	4.87	4.58
Percent of Total Load in Suspension	68	68	90	87	88
Sediment Producing Drainage Area, Square Miles*	1,484	3,264	6,220		11,966
Sediment Yield, Tons per Sq. Mi. per Year	806	331	442		369

* Areas of the drainage basins above major dams and in basalt flow areas are assumed to contribute no sediment.

in 1893, shows the Rio Puerco west of Albuquerque as a relatively small channel on the east side of the valley near the base of Mesita Negra. Aerial photographs taken in 1934 show the Rio Puerco arroyo deeply incised on the west side of the valley with a much larger meander wavelength than the older channel. A similar former channel complete with dead cottonwood trees is reported southeast of Hidden Mountain along the east side of the Puerco valley. The 1934-5 aerial photographs also show that not all of the Rio Puerco was deeply incised even at that time. Downstream from the village of Cabezon, the Rio Puerco was shallow, probably due to the channel being "hung up" on a sandstone ledge. Even major tributaries were not incised or were incompletely incised in the 1930's. Other reaches of the Rio Puerco apparently were still shallow enough to dam with simple structures to divert water for irrigation systems. The last of these dams washed out in 1951.

During the twentieth century the lower Rio Puerco has widened and a floodplain and inner channel has developed within the arroyo, replacing the formerly braided channel that flooded the arroyo from wall to wall. The braided channel still exists in one reach of the upper Rio Puerco, and apparently it is aggrading rapidly along this unstudied reach. Tamarisk (salt cedar) was purposefully planted for erosion control along the Rio Puerco in three areas during the 1920's [Bryan and Post, 1927]. This tree has colonized much of the floodplain and channel margins. Willows and a few cottonwoods also grow along the river.

Entrenchment and incision of the Rio Puerco was not unique. Similar events occurred throughout the Southwest. The entrenchment of the Rio Puerco and other arroyos was coincidental with the beginning of large scale commercial stock raising following the arrival of the transcontinental railways and opening of the markets to the east. Many writers have attributed the excessive erosion to overgrazing and other human influences brought on by these events [Calkins, 1941; Dortignac, 1963] but the causes of arroyo incision are subject to debate.

Bryan and Post [1927] questioned the hypothesis that grazing was the sole cause of gully formation on the Rio Puerco. They stated that a gully existed on the Rio Puerco in prehistoric times as evidenced by buried channels visible in the walls of the present-day arroyo. They also cited evidence for a similar prehistoric arroyo on the Chaco River. Livestock grazing could not have been responsible for these episodes of prehistoric gullying. It is also true that there was extensive and heavy grazing of sheep throughout much of New Mexico during the Mexican and Territorial periods [Carlson, 1969] which did not immediately precipitate disastrous erosion. The observations of Bryan and Post led to a theory that there had been cycles of erosion and deposition on the Puerco and other channels in the past, and that climatic factors essentially controlled these cycles. They postulated that arroyos develop during droughts and fill during wetter periods. While they did not deny that uncontrolled grazing had caused considerable damage, Bryan and Post claimed that this factor provided merely a "trigger pull" to initiate a process of extreme erosion that was already imminent.

More recently, Patton [1976], Elliott [1979], and Meyer [1989] developed descriptive models of arroyo evolution based on the assumption that arroyos develop by headward cutting. According to these models, headward cutting entrenches arroyos while the downstream reaches are in a later stage of development. Arroyos follow a process of initial cutting, widening in braided channels, over widening, deposition of alternate bars, and ultimately development of meandering inner channels, migrating point bars and floodplains stabilized by vegetation. Figure 4 illustrates the sequence of arroyo evolution. This sequence may occur over time as changes at a particular location, or the sequence may represent differences in the character of the arroyo at different locations at a particular point in time. These changes can take place through internal adjustments to sediment transport without the influence of climatic change. The stages and sequence of arroyo development have been modeled in controlled precipitation-landform plots in laboratory experiments.

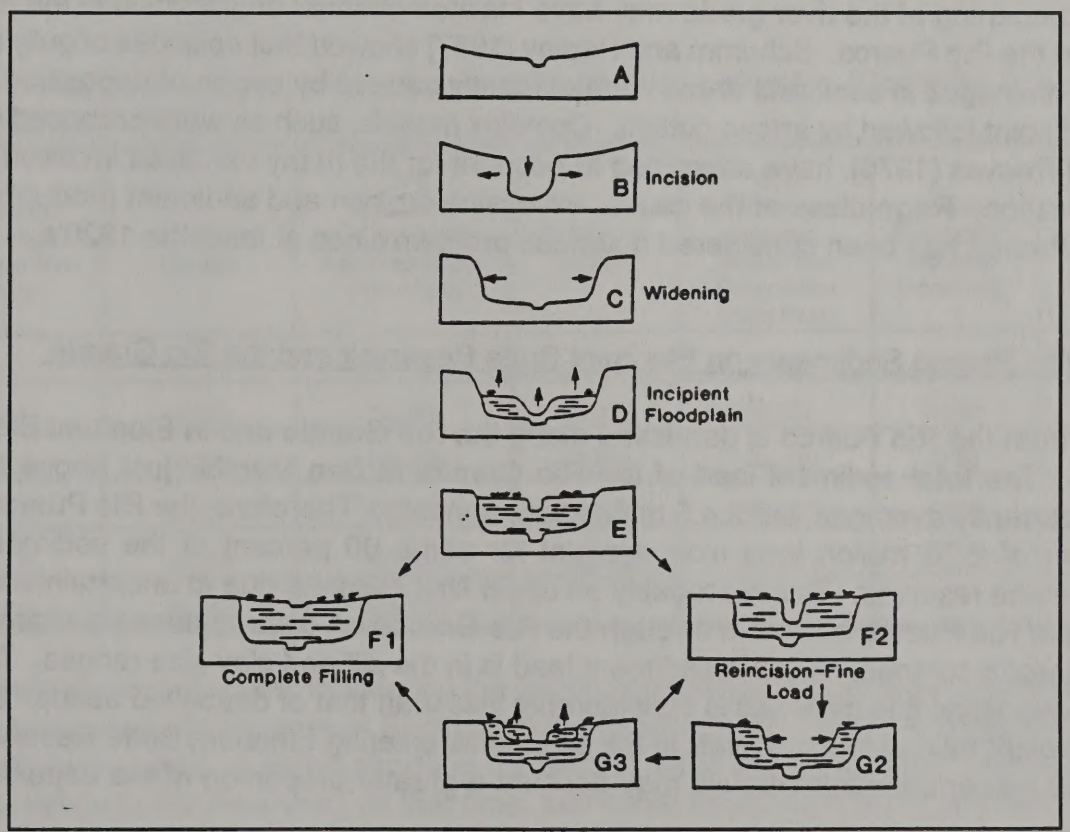

Figure 4: Stages and Sequence of Arroyo Evolution [Gellis, 1991]

Meanwhile Love [1977, 1980, 1983] and Hereford [1984] correlated twentieth-century stream behavior in large drainages (Chaco Wash, Little Colorado River) to climatic and stream discharge changes. According to them, these streams were braided bank to bank until the mid 1930's because of greater precipitation and high discharge events. The

arroyos then narrowed and deposited inner floodplains and banks in response to generally lower discharge, building floodplains as floods overtopped the inner banks.

Webb [1985], Webb and Betancourt [1990] and Hereford [1993] studied the formation of large arroyos by big floods. In each documented case, the immediate cause of entrenchment was a series of unprecedented high discharge events. Overgrazing had occurred either long before the streams downcut or after entrenchment had proceeded.

Other factors have been suggested as contributors to arroyo formation. According to Leopold [1951], increased intensity of precipitation was a significant factor in initiating the gullying process and in the high erosion rates in the semi-arid southwest. Happ [1948] reported that the Rio Grande was shortened by 1-1/2 to 2 miles by the cutoff of a bend of the Rio Grande below the mouth of the Rio Puerco during construction of the railway. The resulting steepening of the river grade may have initiated channel degradation in the Rio Grande and the Rio Puerco. Schumm and Hadley [1957] showed that episodes of gullying on smaller drainages in semi-arid areas were evidently caused by cycles of deposition to a threshold point followed by arroyo cutting. Complex models, such as were proposed by Cooke and Reeves [1976], have attempted to account for the many variables involved in arroyo formation. Regardless of the cause, excessive erosion and sediment production of the Rio Puerco has been considered a serious problem since at least the 1920's.

Effects of Rio Puerco Sediments on Elephant Butte Reservoir and the Rio Grande

Sediment from the Rio Puerco is deposited along the Rio Grande and in Elephant Butte Reservoir. The total sediment load of the Rio Grande at San Marcial, just above the reservoir, currently averages about 4.5 million tons annually. Therefore, the Rio Puerco's contribution of 2.75 million tons may account for some 60 percent of the sediments deposited in the reservoir. This is probably an upper limit estimate due to uncertainties in the routing of Rio Puerco sediment through the Rio Grande. A disproportionate share of the Rio Puerco's contribution to the sediment load is in the silt and clay size ranges. The density of deposited fine materials is considerably less than that of deposited sands. So, while the weight ratio of fine materials in the sediments entering Elephant Butte Reservoir is about 50 percent, these materials may account a greater proportion of the deposited volume.

Deposition of sediment may increase the surface area of a reservoir relative to storage volume resulting in increased loss of water due to evaporation. Table 3 compares the surface area of Elephant Butte Reservoir relative to storage volume for the 1915 and 1988 reservoir surveys. Annual reservoir evaporation has been computed assuming 6 feet of net annual evaporation.

As sediments accumulate in the reservoir, the frequency and magnitude of reservoir spills

can be expected to increase. More water will be spilled or released because storage space is unavailable. The net effect of decreased storage capacity on the future water supply will be primarily determined by the magnitude and patterns of reservoir inflow and by operational decisions. Changes in water uses and infrastructure adaptions may be secondary factors.

The benefit of available reservoir storage capacity is realized when two conditions are met: 1) adequate water is available to fill the reservoir to capacity; and 2) a water shortage follows a full reservoir condition during which the stored water is used to alleviate or prevent the shortage. When adequate water is not available to fill the reservoir, the potential to store water does not have a measurable water supply value; nor does absence of storage affect the water supply when shortages do not develop. Water in storage has value as a recreational and wildlife resource and certain non-use values may apply but these would be difficult to quantify.

Table 3. Reservoir surface area and annual evaporation estimates. [Compiled from Bureau of Reclamation 1988]

Reservoir Storage (Million Acre Feet)	1915 Area (Acres)	1915 Condition Average Annual Net Evaporation (Acre Feet)	1988 Area (Acres)	1988 Condition Average Annual Net Evaporation (Acre Feet)	Annual Evaporation Increase (Acre Feet)	Per Cent Increase
0.1	5,300	31,800	5,000	30,000	-1,800	-6
0.5	12,000	72,000	13,000	78,000	6,000	8
1.0	20,000	120,000	20,800	124,800	4,000	3
1.5	27,800	166,800	28,600	171,600	4,800	3
2.0	33,300	199,800	35,800	214,800	15,000	8
2.5	36,400	218,400	–	–	–	–

The historical record shows that during the period of operation, a shortage closely following a spill has occurred only once at Elephant Butte Reservoir. In 1942, the reservoir filled to capacity and spilled. A water shortage followed in 1951 after a series of years of below normal inflow to the reservoir. At that time, additional water that could have been stored in 1942, if there had been additional reservoir capacity, could have been available to alleviate the shortage. Reservoir storage capacity had decreased by about 400,000 acre feet between 1915 and 1940. If the conditions experienced in the 1940's had occurred with the entire original reservoir capacity available, some 400,000 acre feet of water could have been stored to relieve shortages on a one-time basis. The additional stored water would have been incrementally diminished year by year due to evaporation and other reservoir losses. The normal project storage releases from Elephant Butte and Caballo

Reservoirs as defined by the Rio Grande Compact are 790,000 acre feet annually. Chronic shortages of the 1950's, 60's, and 70's were caused by lack of water flowing into the reservoir and would not have been alleviated by the availability of extra unused reservoir storage capacity.

A numerical model reservoir representing Elephant Butte can be used to estimate the effect that sediment accumulation would have on future water supplies. A model developed for this purpose is described in Appendix F. The model was used to project a worst case scenario in which three severe droughts, like the one experienced in the 1950's, occur during the next century. The model forecasts total water shortages for the different rates of sediment accumulation that would be expected in the reservoir if a sediment control project on the Rio Puerco were or were not undertaken. According to these projections, if a sediment control project were implemented on the Rio Puerco, the additional water that would be available from Elephant Butte Reservoir over the next 100 years can not be expected to exceed a cumulative total of a few hundred thousand acre feet.

Adverse effects of sediment deposition are not strictly limited to the reservoir itself. A significant amount of sediment has been deposited in the Rio Grande channel and floodplain above the reservoir creating increased flood hazards and difficulties in maintaining channels for efficient conveyance of water into the reservoir. Happ [1948] determined that between 1915 and 1936 Elephant Butte Reservoir received 85 percent of the sediment passing the lower end of the floodway.[1] From 1936 to 1940 only 52 percent of the sediment passing the lower end of the floodway reached the reservoir. He attributed the difference to the fact that there had been increasing deposition above the head of the reservoir.

Increased sediment deposition upstream of the reservoir combining with drought conditions created a critical condition in the early 1950's. In some areas the river channel had completely disappeared under deposited sediment and resulting conveyance losses contributed to New Mexico's inability to make water deliveries to Elephant Butte Reservoir as required by the Rio Grande Compact.

By 1951, conveyance losses between San Marcial and the reservoir pool were estimated to be approximately 140,000 acre feet per year and New Mexico's accumulated debit under the Compact exceeded 330,000 acre feet [Bureau of Reclamation, 1953]. These conditions prompted the Bureau of Reclamation to take emergency action under a Presidential order to begin work on the Low Flow Conveyance Channel in 1951. Construction of the Conveyance Channel was completed in 1959. Improvements to the

[1] i.e. the lower end of the Middle Rio Grande Conservancy District levees, which then ended about 14 miles above San Marcial.

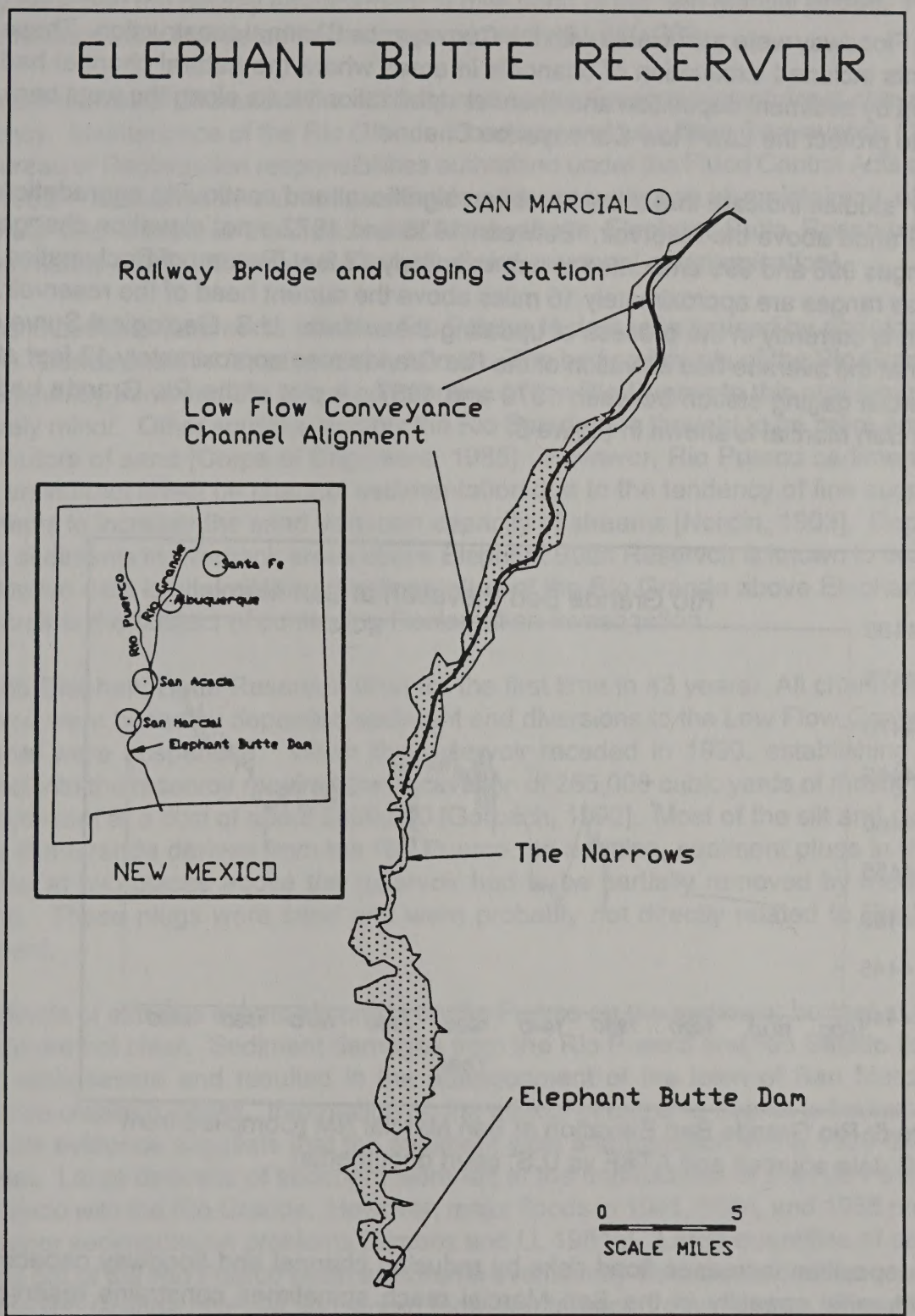

Figure 5: Map of Elephant Butte Reservoir

Rio Grande Floodway were associated with the Conveyance Channel construction. These improvements included excavation of channels in areas where the natural channel had been blocked by sediment deposition and channel stabilization works along the west bank of the river to protect the Low Flow Conveyance Channel.

Reclamation studies indicate that there has been significant and continuing aggradation of the Rio Grande above the reservoir. Between 1936 and 1972 a net elevation change between ranges 998 and 999 amounted to approximately 12 feet [Bureau of Reclamation, 1972]. These ranges are approximately 16 miles above the current head of the reservoir. Reclamation is currently in the process of updating these data. U.S. Geological Survey data show that the average bed elevation of the Rio Grande rose approximately 12 feet at the San Marcial gaging station between 1979 and 1987. A plot of the Rio Grande bed elevation at San Marcial is shown in Figure 6.

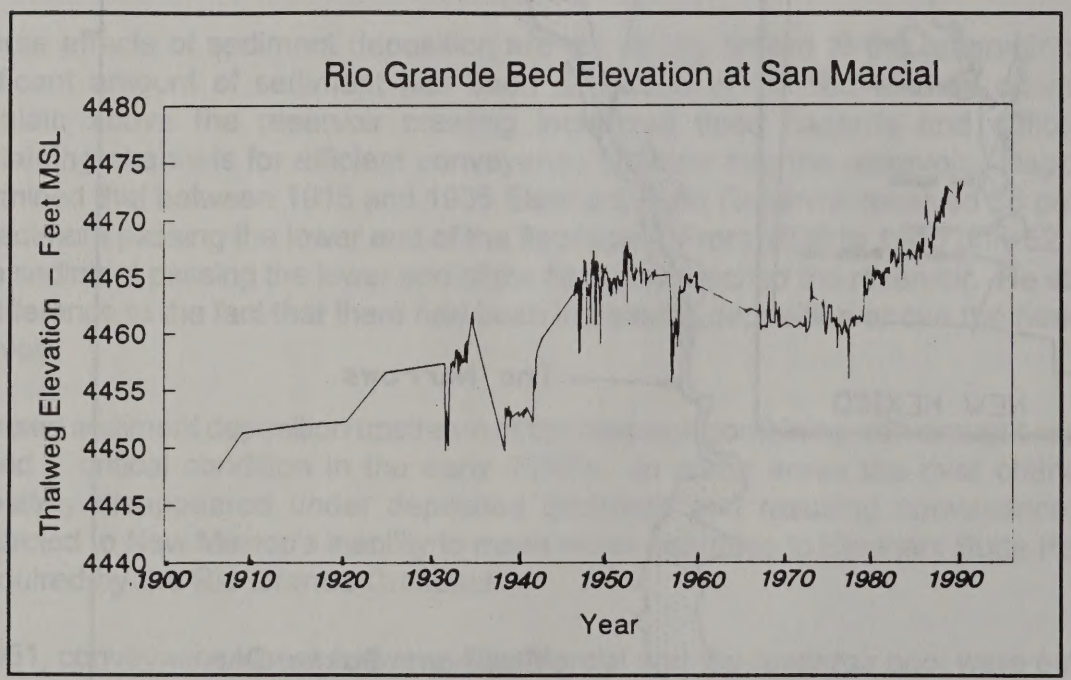

Figure 6: Rio Grande Bed Elevation at San Marcial NM [Compiled from USGS data sources and ATSF vs U.S. court documents]

Sediment deposition increases flood risks by reducing channel and floodway capacity. Reduced channel capacity in the San Marcial reach sometimes constrains reservoir operations at Cochiti Dam and can affect the timing of water deliveries. Over the past ten years, channel aggradation in the San Marcial reach has necessitated the raising of levees in much of the ten mile reach between San Marcial and the reservoir. In 1991, high water

nearly breached the railway embankment ½ mile north of the San Marcial Bridge. Repairs to the railway were estimated to cost approximately $1,000,000.

Sediment deposition increases the difficulty and costs of maintaining channel conveyance efficiency. Maintenance of the Rio Grande Floodway and Low Flow Conveyance Channel are Bureau of Reclamation responsibilities authorized under the Flood Control Acts of 1948 and 1950. Reclamation currently estimates the annual cost of maintaining effective channels and levees in the headwater reach above Elephant Butte Reservoir to be approximately $900,000 per year [Drew C. Baird, personal communication].

The contribution of sediments from the Rio Puerco to damages caused by aggradation of the Rio Grande channel is not precisely known. The bed sediments of the Rio Grande are predominantly sand and the direct contribution of the Rio Puerco to this problem may be relatively minor. Other sources, notably the Rio Salado, are thought to be more important contributors of sand [Corps of Engineers, 1985]. However, Rio Puerco sediments may have an indirect effect on channel sedimentation due to the tendency of fine suspended sediments to increase the sand transport capacity of streams [Nordin, 1963]. Deposition of fine sediments in overbank areas above Elephant Butte Reservoir is known to occur, but quantitative data is unavailable. Sedimentation of the Rio Grande above Elephant Butte Reservoir is the subject of continuing Reclamation investigation.

In 1985 Elephant Butte Reservoir filled for the first time in 43 years. All channels in the reservoir were buried by deposited sediment and diversions to the Low Flow Conveyance Channel were suspended. When the reservoir receded in 1990, establishing a new channel into the reservoir required the excavation of 265,000 cubic yards of mostly silt and clay sediment at a cost of about $800,000 [Gorbach, 1992]. Most of the silt and clay load of the Rio Grande derives from the Rio Puerco. In addition, sediment plugs in the river channel at two places above the reservoir had to be partially removed by mechanical means. These plugs were sand and were probably not directly related to Rio Puerco sediment.

The effects of extreme events occurring on the Puerco on the sediment budget of the Rio Grande are not clear. Sediment damages from the Rio Puerco and Rio Salado floods of 1929 were severe and resulted in the abandonment of the town of San Marcial and extensive cropland losses. Information on the effects of extreme events is limited but the available evidence suggests that the sediment yield and transport in the 1929 flood was unusual. Large deposits of sediment were left at the confluences of the Rio Puerco and Rio Salado with the Rio Grande. However, major floods in 1941, 1954, and 1955 produced only minor sedimentation problems [Simons and Li, 1981c]. Large quantities of sediment coming out of the Rio Puerco basin in extreme events may be deposited at the confluence with the Rio Grande channel and stored for future transport downstream. The effects of this queuing of sediment in the system have not been thoroughly investigated.

Trend in Elephant Butte Reservoir Sedimentation

According to the most recent reservoir survey [Bureau of Reclamation 1988], the remaining capacity of Elephant Butte Reservoir is about 2.06 million acre-feet. Storage has been reduced by 22 percent from the original 1915 capacity of 2.63 million acre-feet. During the life of the reservoir the average rate of sediment deposition has been about 8,000 acre feet per year, but this rate has not been constant. Figure 7 shows that the rate of decrease in reservoir capacity due to deposition of sediment in Elephant Butte Reservoir was as high as 25,000 acre feet per year between 1915 and 1920. Thereafter the rate of sediment accumulation decreased to about 15,000 acre-feet per year from 1920 to 1935 and to about 10,000 acre-feet per year from 1935 to 1940 [Happ, 1948]. Since 1940, reservoir surveys show that reduction in reservoir storage capacity due to sediment accumulation has averaged about 3,200 acre feet per year. At a rate of 3,200 acre feet per year it will take about 300 years to half fill the remaining capacity of Elephant Butte Reservoir. About 40 percent of the sediment that has been deposited in the reservoir to date accumulated in the first 10 years of operation. Nearly 75 percent of the sediment deposited to date had accumulated by 1940. Only about 25 percent of the deposition has accumulated since 1940. Sediment load records for the San Marcial gaging station confirm the decreasing trend in sediment load above the reservoir (see Figures 12 and 13).

The most recent reservoir survey shows that deposition in the reservoir between 1980 and 1988 averaged 5,600 acre feet per year. This was a period of increased reservoir inflow and it is not clear whether an increasing sedimentation trend is indicated. There was also significant deposition in the river and floodplain above the reservoir during this period (See Figure 6).

Reduction of sedimentation in the reservoir can be partly attributed to construction of upstream dams which trap sediment and change the river flow regime, accumulation and storage of sediments in overbank areas and floodplains upstream of the reservoir, and to reduced erosion and sediment production from the drainage basin. The uncontrolled drainage basin area above Elephant Butte Reservoir has been reduced by some 54 percent from 25,923 square miles to 11,966 square miles by construction of dams on the Rio Grande at Cochiti (1975), the Jemez River (1953), and Galisteo Creek (1970). The Rio Puerco now drains about 52 percent of the drainage basin area above Elephant Butte Reservoir that is uncontrolled by dams.

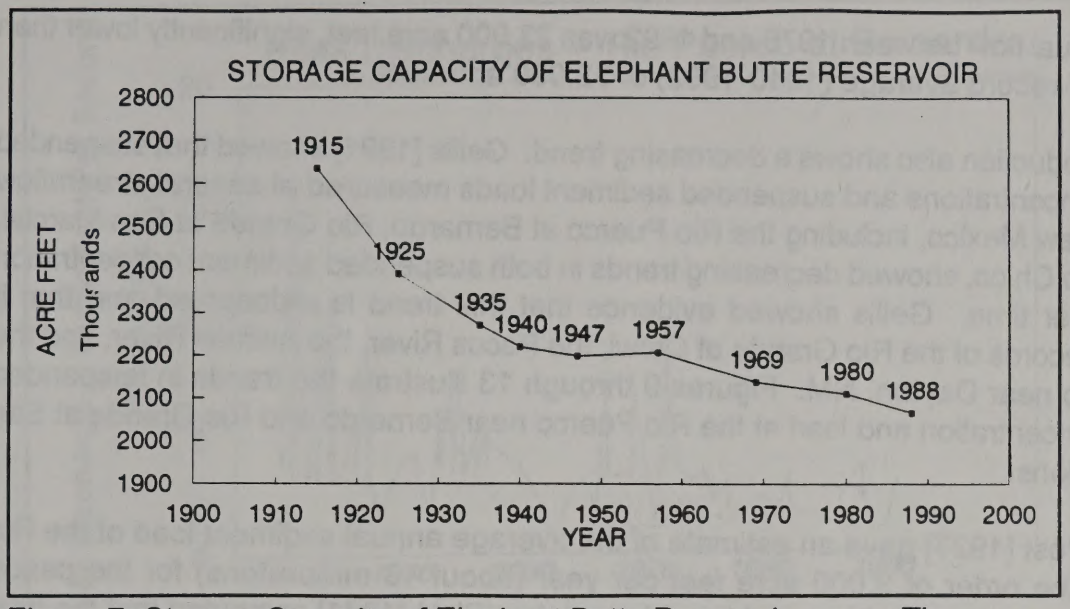

Figure 7: Storage Capacity of Elephant Butte Reservoir versus Time.
[Compiled from Bureau of Reclamation Sediment Survey Records]

Elephant Butte sedimentation records show that relative sediment deposition in the reservoir ranged from 914 tons per square mile of contributing basin per year between 1915 and 1935 to 143 tons per square mile per year between 1935 and 1957. The very low relative rate of sediment deposition in the reservoir from 1935 to 1957 may have been due to high rates of deposition upstream of the reservoir in the channel and floodplains during this period, to very low runoff in some of those years, and to compaction and consolidation of deposited sediments during very low reservoir levels. Currently (average of the period 1976-1992) the average yield of sediment from the uncontrolled Rio Grande basin above San Marcial is about 370 tons per square mile per year. By comparison, the rate of sediment production in the Rio Puerco Basin is approximately 440 tons per square mile per year. These estimates assume 100 percent trap efficiency of reservoirs above Elephant Butte.

Trend in Sediment Yield from the Rio Puerco Basin

Analysis of stream flow records shows that the frequency and magnitude of flood peaks on the Rio Puerco at Bernardo have decreased, most markedly since about 1970 (See Figure 8). Similar trends in the records of Arroyo Chico and Rio San Jose are also evident, though a peak of 6,000 cubic feet per second (cfs) occurred on the Rio San Jose on August 5, 1988. The corresponding peak discharge of the Rio Puerco at Bernardo was 3,750 cfs for that event.

There has also been a trend toward decreased total flow of the Rio Puerco at Bernardo.

Average annual flow between 1976 and 1992 was 23,000 acre feet, significantly lower than the period-of-record average (1940-1992) of 32,000 acre feet.

Sediment production also shows a decreasing trend. Gellis [1991] showed that suspended sediment concentrations and suspended sediment loads measured at several streamflow stations in New Mexico, including the Rio Puerco at Bernardo, Rio Grande at San Marcial, and at Arroyo Chico, showed decreasing trends in both suspended sediment concentration and load over time. Gellis showed evidence that this trend is widespread and that it appears in records of the Rio Grande at Otowi, the Pecos River, the Animas River, and the Rio Penasco near Dayton, NM. Figures 9 through 13 illustrate the trends in suspended sediment concentration and load at the Rio Puerco near Bernardo and Rio Grande at San Marcial Stations.

Bryan and Post [1927] gave an estimate of the average annual sediment load of the Rio Puerco on the order of 9,000 acre feet per year (about 13 million tons) for the period between 1885 and 1927. Simons, Li and Associates (SLA) [1981] computed that the total sediment load of the Rio Puerco at Bernardo averaged 5.1 million tons annually between 1962 and 1972. More recently, between 1976 and 1992, the sediment load at Bernardo has decreased to about half this value. Between 1962 and 1972, the total annual sediment load of the Rio Grande at San Acacia (Floodway and Conveyance Channel Combined) averaged 11.5 million tons. Approximately 44 percent of the total sediment load of the Rio Grande at San Acacia apparently derived from the Rio Puerco during that time; now approximately 60 percent of the Rio Grande's sediment load comes from the Rio Puerco. Proportionally the sediment contribution of the Rio Puerco to the Rio Grande is apparently becoming more significant with time, probably because dams on the Rio Grande (Cochiti), Galisteo Creek, and Jemez River have reduced the Rio Grande's upstream sediment load.

According to SLA calculations, between 1962 and 1972 the average annual sediment load of the Rio Puerco consisted of 0.75 million tons of bed material (i.e. sand) and 4.4 million tons of silts and clays. The sediment load the Rio Grande at San Acacia (Floodway and Conveyance Channel combined) consisted of 4.8 million tons of bed material and 6.7 million tons of silt and clay load. Accordingly, the Rio Puerco contributed 16 percent of the bed material load at San Acacia and 66 percent of the silt and clay load during the 1962 to 1972 period. Concurrently at San Marcial, the load of the Rio Grande (combined) was 36 percent bed material and 64 percent fine materials. A study by the Bureau of Reclamation [1990a] indicates that more recently the sediment load of the Rio Grande at San Marcial is approximately half sand and half silts and clays.

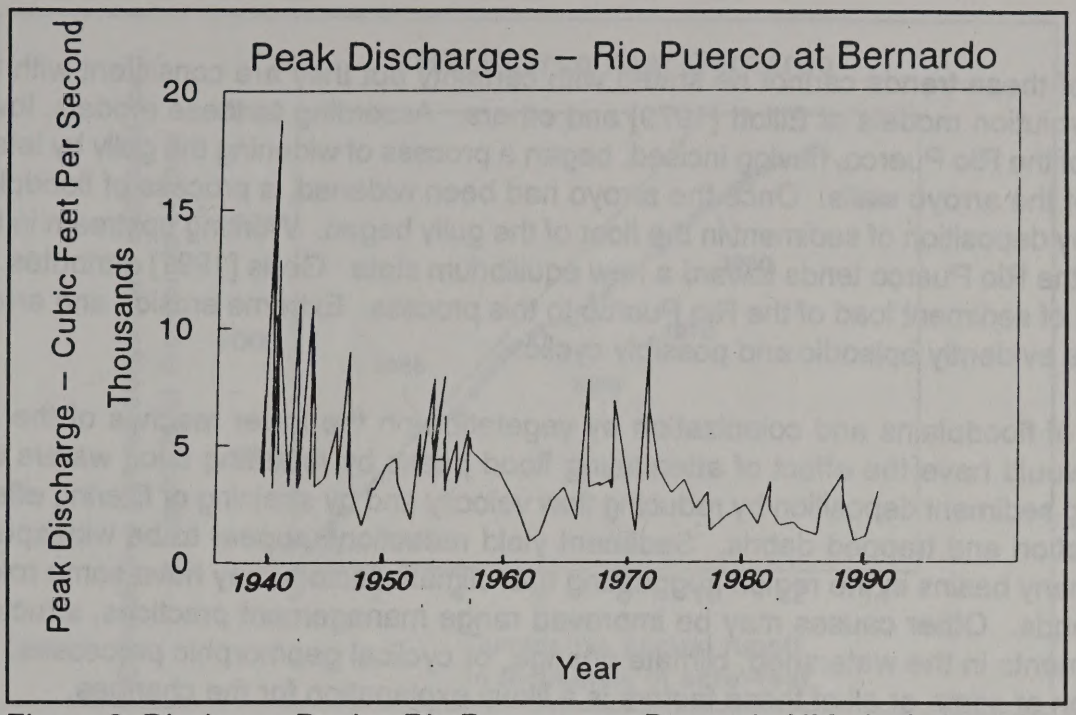

Figure 8: Discharge Peaks, Rio Puerco near Bernardo NM. Includes all annual peaks plus all peaks over 2,000 cfs. (USGS records]

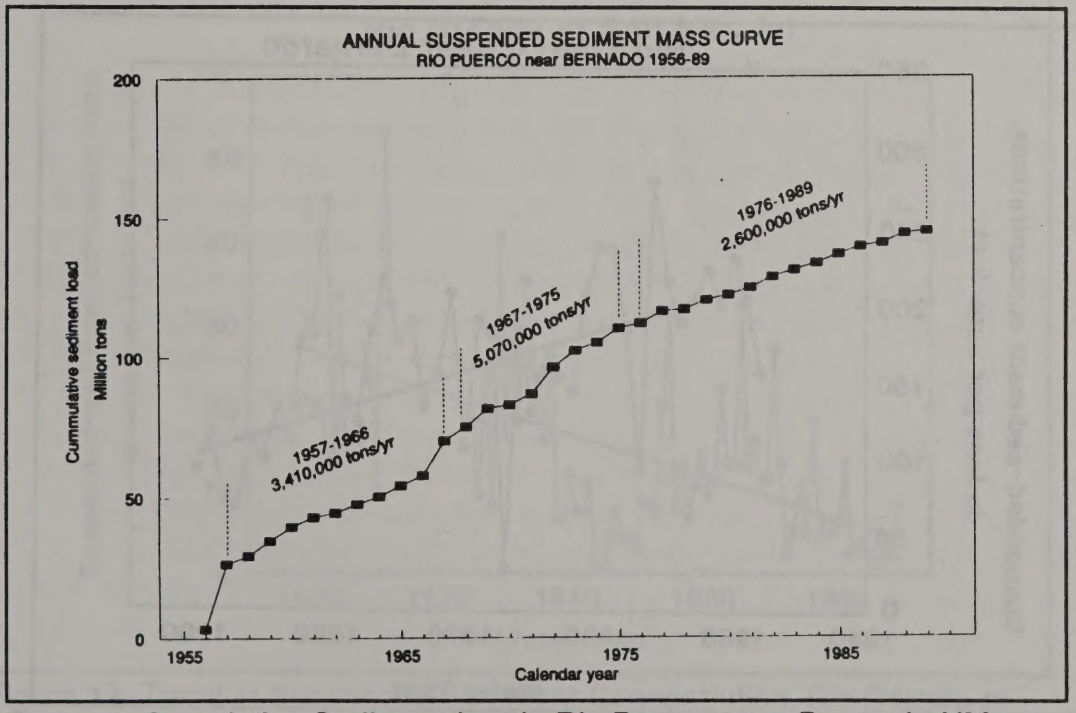

Figure 9: Cumulative Sediment Load. Rio Puerco near Bernardo NM [USGS records]

Causes of these trends cannot be stated with certainty but they are consistent with the arroyo evolution models of Elliott [1979] and others. According to these models, lower reaches of the Rio Puerco, having incised, began a process of widening the gully by lateral erosion of the arroyo walls. Once the arroyo had been widened, a process of floodplain building by deposition of sediment in the floor of the gully began. Working upstream in this manner, the Rio Puerco tends toward a new equilibrium state. Gellis [1991] attributes the reduction of sediment load of the Rio Puerco to this process. Extreme erosion and arroyo incision is evidently episodic and possibly cyclic.

Building of floodplains and colonization by vegetation on the lower reaches of the Rio Puerco would have the effect of attenuating flood peaks by retarding flood waters and promoting sediment deposition by reducing flow velocity and by straining or filtering effects of vegetation and trapped debris. Sediment yield reductions appear to be widespread among many basins in the region suggesting that climatic factors may have some role in these trends. Other causes may be improved range management practices, structural improvements in the watershed, climate change, or cyclical geomorphic processes. An interaction of some or all of these factors is a likely explanation for the changes.

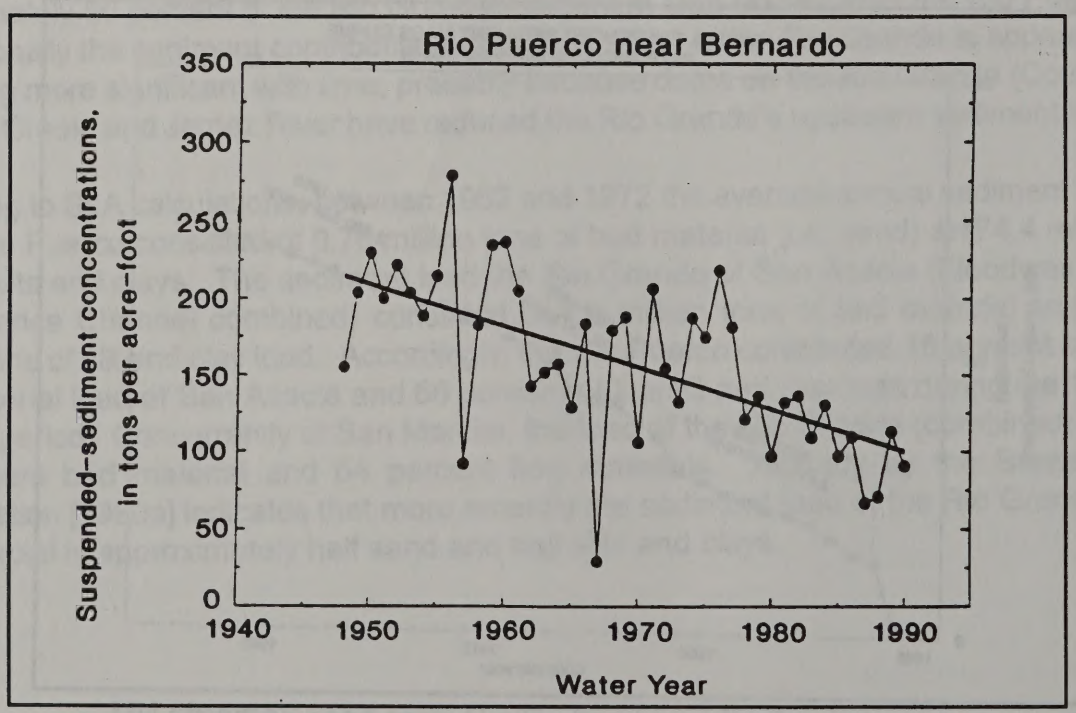

Figure 10: Trend in Suspended Sediment Concentration. Rio Puerco near Bernardo [Gellis, 1991]

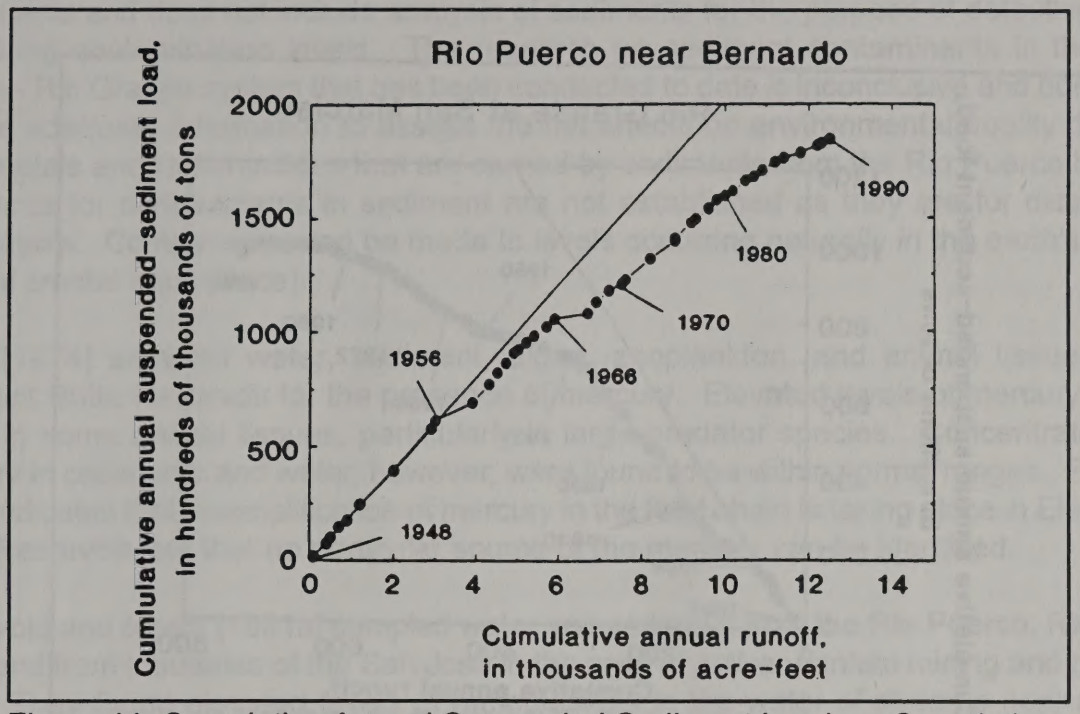

Figure 11: Cumulative Annual Suspended Sediment Load vs. Cumulative Annual Runoff. Rio Puerco near Bernardo [Gellis, 1991]

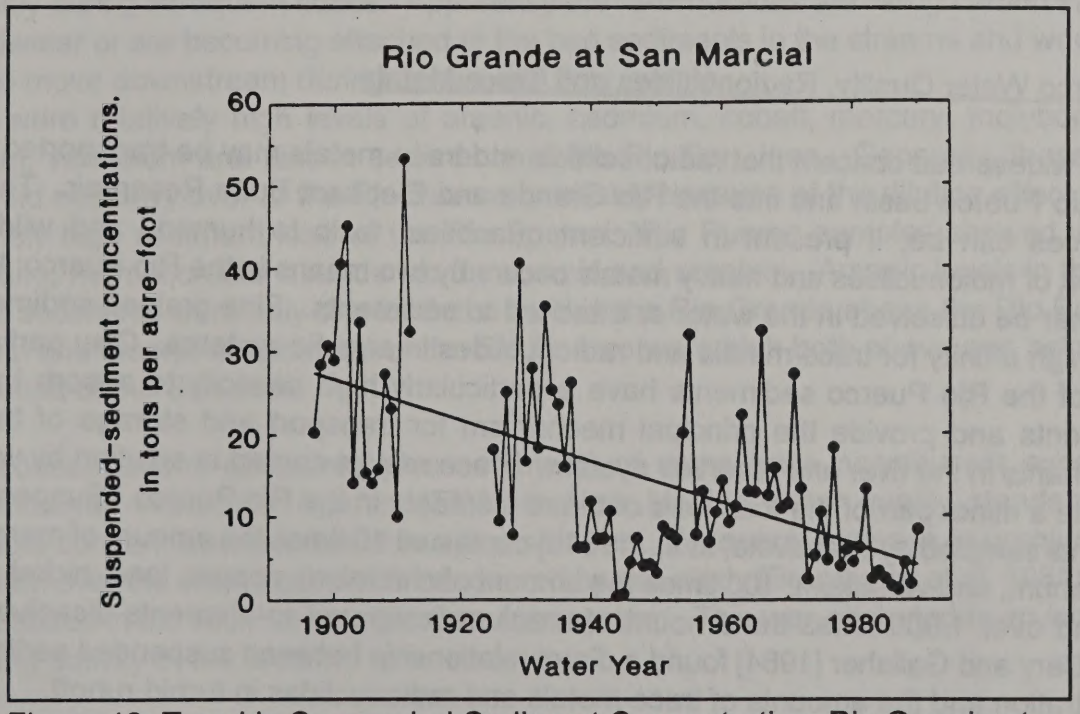

Figure 12: Trend in Suspended Sediment Concentration. Rio Grande at San Marcial [Gellis, 1991]

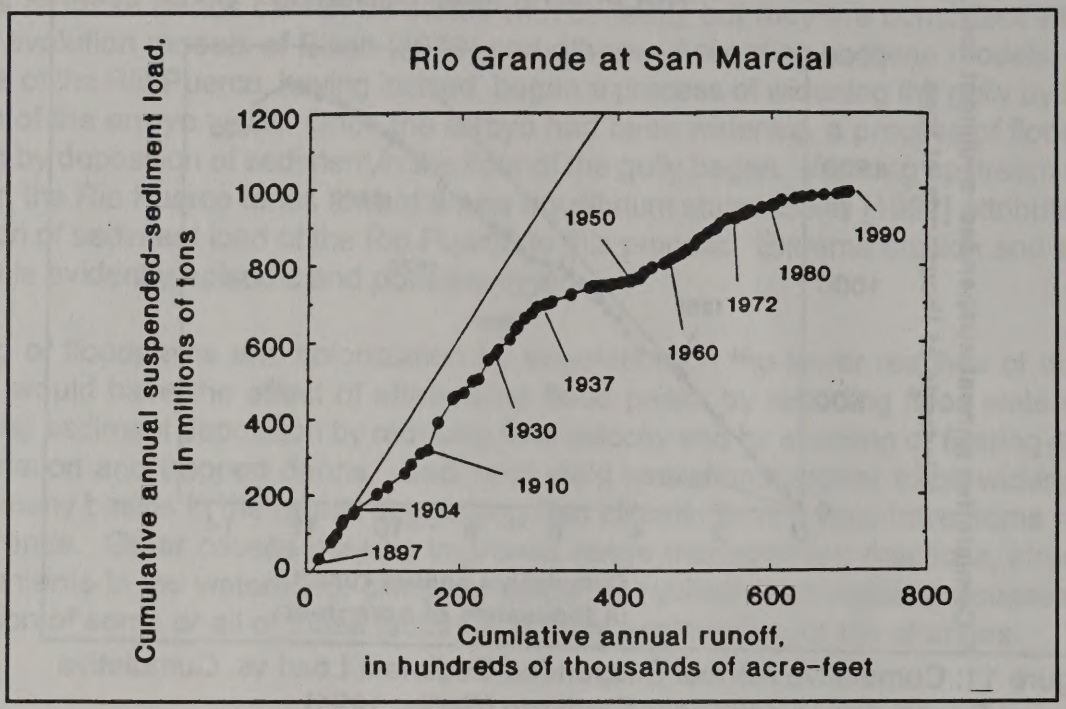

Figure 13: Cumulative Annual Sediment Load vs. Cumulative Annual Runoff. Rio Grande at San Marcial [Gellis, 1991]

Rio Puerco Water Quality, Radionuclides and Trace Metals

There is widespread concern that radionuclides and trace metals may be transported out of the Rio Puerco basin and into the Rio Grande and Elephant Butte Reservoir. These substances can be, if present in sufficient quantities, toxic to humans and wildlife. Transport of radionuclides and heavy metals occurs by two means in the Rio Puerco; they may either be dissolved in the water or attached to sediments. Fine grained sediments have a high affinity for trace metals and radionuclides in aquatic systems. Clay particles typical of the Rio Puerco sediments have a particularly high capacity to adsorb these constituents and provide the principal mechanism for transport and storage of these contaminants in the river and reservoir system. Trace metals carried in solution by water constitute a minor part of the total load of these elements in the Rio Puerco. Suspended sediments sampled by Brandvold, et al. [1981b] contained 10 times the amount of mercury, molybdenum, and vanadium, 100 times the amount of chromium, copper, lead, nickel, and zinc, and over 1,000 times the amount of uranium compared to elements dissolved in water. Cary and Gallaher [1984] found a direct relationship between suspended sediment concentration and the amounts of trace metals and radionuclides in turbid runoff.

Regular water quality sampling is conducted on the Rio Puerco at Bernardo and at other stations in the basin. This sampling is done only to detect the presence of dissolved

constituents and does not include analysis of sediments for the purpose of detecting and measuring contamination levels. The research on sediment contaminants in the Rio Puerco - Rio Grande system that has been conducted to date is inconclusive and does not provide adequate information to assess the net effects on environmental quality due to trace metals and radionuclides that are carried by sediments from the Rio Puerco basin. Standards for contaminants in sediment are not established as they are for dissolved constituents. Comparisons can be made to levels occurring naturally in the earth's crust (normal crustal abundance).

Popp [1974] sampled water, sediment, algae, zooplankton, and animal tissue from Elephant Butte Reservoir for the presence of mercury. Elevated levels of mercury were found in some animal tissues, particularly in large predator species. Concentration of mercury in sediments and water, however, were found to be within normal ranges. Popp's study indicates that bioamplification of mercury in the food chain is taking place in Elephant Butte Reservoir, but that no particular source of the mercury can be identified.

Brandvold and others [1981a] sampled water and sediment from the Rio Puerco, Rio San Jose, and from tributaries of the San Jose in the area of active uranium mining and milling sites. They found elevated levels of radionuclides in the water of streams near active uranium mining and milling sites, but the elevated levels of radionuclides did not appear in the Rio San Jose itself. The fate of these radionuclides is not known. Surface waters from the areas where the elevated radionuclide levels were detected reach the Rio San Jose only during infrequent floods. Apparently the radionuclides are being carried into the groundwater or are becoming attached to the bed sediments in the streams and would be likely to move downstream during ephemeral flow events.
There were relatively high levels of arsenic, cadmium, cobalt, mercury, molybdenum, uranium, vanadium and zinc in sediments of the Rio San Jose. Generally, these high levels did not carry over to the Rio Puerco, probably because of the diluting effect of the extremely high sediment load of the Rio Puerco. Rio Puerco samples showed values exceeding normal crustal abundance for arsenic and uranium. Arsenic levels in the Rio Puerco sediments were only one tenth the level in the Rio Grande above the Rio Puerco. Uranium and arsenic in sediment of the Rio Puerco were high both above and below the confluence of the San Jose.

Total concentrations (dissolved plus sediment) of some trace constituents exceeded Environmental Protection Agency (EPA) or New Mexico water quality standards for allowable concentrations in water in a few samples. A general increase in uranium and vanadium over the short period of time covered by this study [Brandvold, et al. 1981a] was also detected in the Rio Puerco - Rio San Jose system. This was attributed to an increase in mining activity in the area.

Sampling for the study by Brandvold and others [1981b] was limited and does not provide adequate data to show the net effects of radionuclide and trace metal contribution from the

Rio Puerco to the Rio Grande, nor did the scope of the investigation cover potential environmental effects in the Rio Grande or Elephant Butte Reservoir. The relative contributions of sources of radionuclides and trace metals in the Rio San Jose - Rio Puerco system are unknown and the effects of the episodic nature of flow in the system warrants more detailed and intensive study.

Popp, Love, Hawley, and Novo-Gradac [1984] found elevated levels of radionuclides and of arsenic, selenium, cadmium, mercury, and uranium in oxbow sediments of the Rio Puerco. They did not find evidence of increased levels between pre- and post-1950 deposits, indicating a significance of non-point sources for these elements relative to sites of mining activity.

Ong, O'Brien and Rucker [1991] studied bottom sediments deposited in the Rio Grande, and in canals, marshes, and irrigated fields in the Bosque del Apache National Wildlife Refuge. They reported possible elevated levels of cadmium, lead, manganese, and radium-226 in bottom sediment samples. Trace element concentrations found in biological samples were less than reporting limits or within normal background levels.

With the exception of Popp's [1974] sampling for mercury, sediments in Elephant Butte Reservoir have not been sampled to determine the presence of radionuclides and trace metals. Mechanisms of contaminant exchange between sediments and the environment in a given case cannot be established without detailed investigation. Factors influencing these mechanisms are specific to the nature of the contaminants and sediments, and the biological and chemical environments in which they exist. Speciation studies and investigation of the environments in which the sediments are deposited and stored is necessary to assess the potential for exchange of trace metals and radionuclides between sediments and the environment.

CONCLUSIONS

Conclusion 1

Available data and information indicate that there is not justification to pursue further investigation of a sediment control project on the Rio Puerco at the present time. Based on historical data, current conditions, and apparent trends, there are significant uncertainties regarding the net water supply and economic benefits that could accrue to the Rio Grande and Elephant Butte Reservoir from a Rio Puerco sediment control project. This conclusion applies to a perspective of 50 to 100 years and does not preclude the possibility that such a project may become justifiable in the future. The following forecasts and estimates are the basis for this conclusion:

Expected sediment deposition in Elephant Butte Reservoir in the next 100 years: Sediment deposition in Elephant Butte Reservoir has averaged 3,200 acre feet per year since 1940. Between the two most recent surveys in 1980 and 1988 this rate was about 5,600 acre feet per year. With no action, 300,000 to 500,000 acre feet of sediment can be expected to deposit in the Reservoir in the next 100 years. Available options for reducing the contribution of sediment from the Rio Puerco would not result in a reduction of reservoir sedimentation sufficient to justify a costly project on the Rio Puerco.

Rio Puerco sediment reduction on the order of 30 to 75 percent could probably be achieved by implementing a sediment control project. Because the Rio Puerco accounts for about 60 percent of Rio Grande sediments, the sediment load in the Rio Grande would thereby be reduced by about 20 to 45 percent.

A sediment control project on the Rio Puerco could reduce sediment deposition in Elephant Butte Reservoir by as much as 225,000 acre feet (45% of 500,000 acre feet) in the next 100 years. For comparison, the sediment storage allocation for the Hidden Mountain Dam proposed by the Corps of Engineers on the Rio Puerco west of Los Lunas was 210,000 acre feet [Corps of Engineers, 1985]. With a sediment control project in place on the Rio Puerco, deposition in Elephant Butte would still amount to between about 165,000 (55% of 300,000) and 400,000 (80% of 500,000) acre feet.

Storage capacity at the end of 100 years would probably be between 1.5 and 1.7 million acre feet without a sediment control project, and between 1.6 and 1.8 million acre feet with a project. At the average rate of sediment deposition for the 48 year period of 1940 to 1988, the remaining reservoir capacity will be half filled in about 300 years.

Expected increased frequency of reservoir spills: Reservoir spills will become more frequent as sediment deposits accumulate in the reservoir. Historically, the reservoir has operated at or above 1.5 million acre feet about 20 percent of the time and at or above 1.8 million acre feet about 10 percent of the time. A sediment control project on the Rio Puerco might reduce the probability of spills at the end of the next century by about 10 to 15 percent.

The quantity of additional water that would be available below Elephant Butte Dam because of a sediment control project on the Rio Puerco can be projected by simulating reservoir operations. A simple model for simulating operations is described in Appendix F. The operation model was used to evaluate a "worst case" scenario, in which three severe droughts occur in the next century. The total cumulative water supply benefit from reduced reservoir spills attributable to a Rio Puerco sediment control project would not be likely to exceed a cumulative total of 200,000 acre feet, distributed over the next 100 years.

Expected evaporation losses: For a given storage volume, the surface area of Elephant Butte Reservoir has increased somewhat due to sediment deposition. Between 1915 and 1988, this increase was less than 10 percent. Recognizing that the increase in surface area relative to storage volume depends on many factors, rough proportional estimates of future increases in evaporation can be projected.

Without a sediment control project on the Rio Puerco, annual evaporation from the reservoir at the end of the next century may average about 10,000 acre feet greater than it now does. Assuming for simplicity a linear rate of increase, during the next 100 years the total cumulative increase in evaporation from the reservoir due to additional sediment accumulation would be around 500,000 acre feet.

A sediment control project could reduce the increased evaporation from Elephant Butte to about 5,000 acre feet per year at the end of 100 years. For the 100 year period, this would amount to about 250,000 acre feet. The Corps of Engineers [1985] estimated that water losses from the Hidden Mountain Reservoir would average 6,600 acre feet per year, or 660,000 acre feet over 100 years. Alternative sediment control projects would also reduce runoff to some degree. Runoff reductions due to alternative sediment control projects cannot be estimated without extensive further investigation but are assumed to be of similar magnitude.

The total increase in evaporation losses for the system over 100 years would be on the order of 500,000 acre feet per year without a project, and more than 900,000 acre feet if a sediment control project were implemented. In common sense terms, evaporation from a relatively shallow reservoir on the Rio Puerco or increased consumptive uses resulting from alternative sediment control projects would likely exceed evaporation losses from Elephant Butte Reservoir.

Channel maintenance requirements: The Rio Grande carries a concentration of sediment that is among the highest of the world's rivers. Deposition of this sediment upstream of and in Elephant Butte Reservoir will require significant work on a continuing basis to maintain channels for delivery of water into the reservoir. Continued aggradation of the Rio Grande may eventually threaten communities upstream of the reservoir and the Bosque del Apache National Wildlife Refuge. Reclamation now estimates that the yearly cost of channel and levee maintenance in the San Marcial reach is about $900,000 [Drew Baird, pers. comm.]. The contribution of sediments from the Rio Puerco to this problem cannot easily be quantified. Ongoing Reclamation investigations may help to clarify the influence of the Rio Puerco in channel and floodplain aggradation.

Sediment control on the Rio Puerco might provide some channel maintenance cost reductions, but these would probably not represent a cost effective benefit. Most sediments deriving from the Rio Puerco are fine silts and clays which generally are carried suspended in the flow and tend to deposit in the lower delta areas and in the reservoir pool. Coarser sediments from the Rio Salado and other sources were thought by the Corps [1985] to be a more significant cause of channel aggradation.

Extraordinary maintenance will be required on a periodic basis to open channels to the reservoir during times of falling storage levels. Cost of this maintenance cannot be accurately estimated. Drawing on recent experience, expenditure for this type of maintenance in 1991 was about $800,000. Work of this type might be required every 10 years or so, on the average. A small incremental reduction in these costs due to a sediment control project on the Rio Puerco would probably not be cost effective.

Other Considerations: Elephant Butte Reservoir represents a significant recreational resource with attendant economic benefits. Level of use depends largely on surface area and shoreline length. In the foreseeable future, rising and falling reservoir levels due to varying inflow would likely be a more important factor in determining recreational use of the reservoir than sediment accumulation. Recreational benefits at other sites due to a Rio Puerco sediment control project would be incidental.

Depending on the alternative, fish and wildlife values could be enhanced with a sediment control program in the Rio Puerco drainage. The biological resources of Elephant Butte Reservoir would not be measurably affected. The Rio Grande channel and the riparian corridor below the Rio Puerco benefit from flood discharges that would be attenuated by sediment control structures. The environmental values within the Rio Puerco drainage would benefit, however, from any sediment control program because water would be retained and consumed, to some degree, within the watershed.

Flood control benefits could not be used to justify a sediment control project on the Rio Puerco because the Corps has determined that an improved levee system below San Acacia would be a more cost effective means of providing flood protection. Benefits associated with reduction of damage to infrastructure facilities due to incremental reduction in sediment load from the Rio Puerco cannot be easily estimated but would be relatively minor.

The lack of justification for a sediment control project at present does not imply that such justification will not arise later. Changes in economic or hydrologic conditions and continued accumulation of sediment in Elephant Butte Reservoir may create circumstances more conducive to development of a project at a later time. A range of possible sediment control alternatives was identified during the course of this investigation. Appendix A contains a discussion of these alternatives.

This conclusion should not be construed to mean that sediments do not present significant problems for maintenance and management of the Rio Grande and Elephant Butte Reservoir. Nor does this conclusion mean that soil erosion in the Rio Puerco watershed does not present serious resource problems in the basin.

Conclusion 2

Evidence exists that heavy metal and radionuclide contaminants are carried into the Rio Grande by the Rio Puerco. The majority of these contaminants are attached to sediment particles and carried with the sediment load. Existing regular water quality sampling on the Rio Puerco does not include analysis of sediments for presence and concentration of contaminants. Research on the types, sources, and quantities of contaminants that are carried attached to sediments is limited and inconclusive. It is not known whether the Rio Puerco contributes trace metals or radionuclides to the Rio Grande in quantities sufficient to cause health risks to humans or adverse ecological effects. Very little is known about the chemical and biological environments in which these sediments are deposited. It is also not known whether slugs of contaminants are or could be introduced to the Rio Grande during flood events. These are important considerations in determining the potential for mobilization of these substances into the food chain or the environment.

RECOMMENDATIONS

Recommendation 1

Implement a sampling and analysis program designed to evaluate the net effect of sediments contaminated by trace metals and radionuclides from the Rio Puerco on the Rio Grande, Elephant Butte Reservoir, and associated ecosystems. A more comprehensive study should be done to determine whether trace metals and radionuclides are present in quantities and in forms that might pose significant health risks to humans or animals now or in the future. The sampling program should include sampling in the Rio Puerco basin adequate to locate and characterize contaminant sources. Sampling is needed over a wide range of flow conditions to account for the episodic and ephemeral flow of the Rio Puerco.

Potential for mobilization of contaminants attached to sediments depends on the chemical form of the substance and the chemical and biological environment in which the sediments exist. An analysis of these factors is needed to provide a conclusive assessment of the extent and degree of the hazard posed by contaminated sediments.

Recommendation 2

Successfully managing the Rio Grande basin over the long term to optimize water use, reduce sedimentation problems, and improve water quality will require cooperation, adequate planning, and sufficient data and information to support decision making. The Rio Puerco basin is a dynamic system responding constantly to climate trends, management decisions, and other influences. Although a major investment in sediment control on the Rio Puerco does not appear justified at this time, in a context of broad water resource management issues, Reclamation, other water resource managers, and water users have a significant stake in the condition and management of the Rio Puerco basin as it affects the Rio Grande and Elephant Butte Reservoir in the long term.

Basic data is needed to monitor the basin to detect trends or cycles and to support future management decisions. Long term data collection is essential to developing an understanding of the basin and its governing processes.

Unfortunately, maintenance of several streamflow gaging stations in the Rio Puerco basin has been discontinued in recent years. Rio Grande Basin water managers are confronted

with the need to make increasingly critical decisions on the basis of lacking or out of date information. The quality of future management decisions will depend on the quality of information available.

Continuation and expansion of basic data collection activities is recommended. At a minimum, good streamflow, sediment load, and water quality records from a number of sites are needed for the benefit of present and future managers. New remote sensing, geographic information (GIS), and automated data collection technologies should be used as fully as possible to improve data acquisition and management.

Research into site-specific methods for controlling erosion and managing sedimentation processes is also needed. Knowledge of the costs, benefits, and effectiveness of watershed treatment practices and smaller-scale structural sediment controls is very limited. A better evaluation of past erosion control efforts should be done. Basic maintenance is also needed on many existing sediment control features in the upper watershed.

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APPENDIX A: SEDIMENT CONTROL ALTERNATIVES

General

Reduction of sediment yield from the Rio Puerco basin could be accomplished either by reducing erosion or by inducing controlled deposition in selected areas. Sediment is eroded and transported by moving air or water. Deposition of sediment occurs where the transporting air or water stops or slows. Erosion can be prevented by maintaining the velocity and energy in flowing water below erosive levels or by providing protection to erodible materials. Stopping or slowing moving water or air carrying sediments causes deposition of the sediment.

The most effective strategies for reducing sediment yield from the Rio Puerco would work in concert with natural geomorphic processes to promote desirable trends. These strategies would be least costly, minimally disruptive, and most effective. It is critically important that treatment strategies for the Rio Puerco basin include adequate geomorphic evaluation as a criterion for concept, design, and execution.

The alternatives discussed in this appendix are:

Alternative A: A large dam on the lower reach of the Rio Puerco,

Alternative B: A number of smaller dams or sediment barrier structures at various sites in the watershed,

Alternative C: Low grade control structures on the Rio Puerco and major tributaries,

Alternative D: Watershed treatment and management,

Alternative E: Management of sediment at the head of Elephant Butte Reservoir.

In general all options for reducing sediment yield at the mouth of the Rio Puerco basin would have potential detrimental effects.

All of the proposed options except Alternative E could reduce the runoff of water from the Rio Puerco to some degree by increasing evaporation or consumption by vegetation in the basin. Alternative E would likely result in some increased evaporative loss of water in Elephant Butte Reservoir.

Reduction of sediment load in the Rio Grande could result in some changes to the river. Increased bank erosion, lateral migration of the river, and incision of the channel are possible results of reducing sediment load to the Rio Grande. Sediment from these sources might partially offset the reduced sediment supply from the Rio Puerco. Anticipated benefits from reduction of channel maintenance

required at the head of Elephant Butte Reservoir may be partially offset by increased requirements for bank stabilization in the Socorro Reach.

Conversely, because sediments are a principal cause of the Rio Grande's dynamic behavior, reduction of sediment load in the Rio Grande might result in some decrease in bank erosion and accretion of bars or islands. This effect could produce undesirable results for the biological health of the Rio Grande and the Rio Grande bosque. Soils of the Rio Grande bosque derive from the deposited sediments and reducing or eliminating floods would have a detrimental impact on the bosque ecosystem.

Alternative A: Lower Reach Dam

A large dam on the lower reach of the Rio Puerco could provide effective sediment control by impounding water and allowing sediment to deposit in the reservoir behind the dam. The U.S. Army Corps of Engineers (Corps) has made a detailed study of damming the Rio Puerco to provide flood control for the Rio Grande Valley [Corps of Engineers, 1985]. The dam proposed by the Corps was expected to reduce sediment discharge of the Rio Puerco by almost 65 percent over 100 years. In the final analysis however, the Corps determined that flood control in the Rio Grande Valley between the San Acacia and Elephant Butte Reservoir could be more economically provided by improving the levees between San Acacia and Elephant Butte Reservoir. Providing effective flood control also depended on a dam on the Rio Salado. A suitable dam site on the Rio Salado could not be located because the U.S. Fish and Wildlife Service Sevilleta National Wildlife Refuge could not accommodate the dam and reservoir.

The Corps identified a potential dam site at mile 18 above the mouth of the Rio Puerco. A site further upstream at mile 42 considered in an earlier investigation [Corps of Engineers, 1972] is on Indian land. The dam proposal was unacceptable to the Isleta and Laguna Pueblos without certain conditions including a permanent reservoir pool suitable for recreational purposes. The Corps determined that a permanent pool would be impractical given the hydrology of the Rio Puerco and the mile 18 site, which is mainly on private property, was selected.

Among the advantages of a lower reach dam for sediment control on the Rio Puerco would be the predictability of the effects and results. The proximity of the dam to the mouth of the Rio Puerco would eliminate much of the uncertainty associated with the alternatives. The effectiveness of the dam for reducing sediment in the Rio Grande would not depend on the source of the sediment, processes of sediment transport in the basin above the dam, land use practice in the basin, or other upstream factors.

Other benefits would include an increased margin of flood protection for the Rio Grande Valley between the Rio Puerco and Elephant Butte Reservoir. However, justification of the project on this basis would be difficult in view of the Corps decision that the levees would be a more cost effective way of providing this protection.

According to the Corps proposal, about 95 percent of the benefits that would be realized by damming the Rio Puerco and Rio Salado were attributed to flood control. Only about 5 percent of the benefits were attributable to sediment control and water salvage. Conservation of storage capacity in Elephant Butte Reservoir, agricultural productivity benefits, and impacts on recreation were anticipated by the Corps to be of negligible significance. Under the assumptions made by the Corps a dam on the Rio Puerco for sediment control would not appear to be economically justifiable.

Benefits of a lower reach dam would be limited to downstream populations and users. This alternative would not address erosion and sediment control problems higher in the watershed.

Although a reservoir could be built to store a large amount of sediment, its useful life would be finite and the relative quantity of sediment stored would be limited in relation to the capacity of Elephant Butte Reservoir. To illustrate, assume that a dam on the Rio Puerco stores 210,000 acre feet of sediment as the proposed Corps dam would have done. At the present rate of sedimentation in Elephant Butte Reservoir, 3,200 acre feet per year, about 65 years would be added to the life of Elephant Butte Reservoir by storage of 210,000 acre feet of sediment upstream. Assuming present conditions, half the remaining storage capacity of Elephant Butte Reservoir will be filled by the year 2300. A 210,000 acre foot sediment reservoir on the Rio Puerco would postpone the date by which the reservoir would become half filled until about 2365.

Water would be lost from a reservoir on the Rio Puerco by evaporation, seepage, and phreatophyte consumption. Because the reservoir on the Rio Puerco would be relatively shallow, evaporation losses would be greater than at Elephant Butte. The sediments deposited in and above the Rio Puerco reservoir would create an ideal environment for spreading salt cedar, an undesirable exotic phreatophyte.

Acceptable dam sites on the lower Rio Puerco are limited and construction of a dam would preclude the use of a suitable site in the future. A more critical need for a sediment control dam may arise in the future as sediment deposition in Elephant Butte Reservoir approaches a threshold that severely impacts reservoir operations or if climate or hydrologic conditions change.

The lower reaches of the Rio Puerco probably do not contribute greatly to the sediment discharged to the Rio Grande. Indeed these may be areas experiencing aggradation and deposition and may be effectively trapping sediments without the employment of structural

measures. Construction of a dam in the lower reaches of the Rio Puerco would inundate areas already trapping sediment in the natural process of floodplain building.

A dam operated for effective sediment control would reduce or eliminate flood peaks on the Rio Grande due to the Rio Puerco. The Bosque Biological Management Plan [Crawford et al, 1993] recommends that water management activities be designed to mimic natural hydrographs to the degree possible to support and improve the riverine and riparian habitat along the Rio Grande. A major dam on the lower Rio Puerco could conflict with this objective.

Because of the large area needed for a reservoir and the high density of cultural resources along the Rio Puerco, significant cultural resource impacts would be anticipated. The Corps found that other environmental impacts at the Hidden Mountain Reservoir site would be minor.

A major dam would require a large capital investment and ongoing operation and maintenance. The Corps of Engineers estimated in 1985 that the Hidden Mountain Dam would cost approximately $60,000,000 to construct. Annual costs were calculated to be $4,884,000 including amortization and interest on the investment (8.125% for 100 years) and operation, maintenance, and replacements ($170,000 annually).

Alternative B: Sediment Barrier Structures

This alternative would entail construction of a number of smaller dams at selected sites along the Rio Puerco and on major tributaries. These dams would not be designed to impound water, but to retard and attenuate floods, induce deposition of sediments upstream, and create conditions conducive to channel aggradation. Essentially this alternative would enhance the natural process of floodplain building that is currently reducing sediment yield from the Rio Puerco basin.

Specially managed areas upstream of structures would help to produce riparian zone conditions favorable for sediment trapping and deposition, floodplain building, flood attenuation, wildlife habitat, and controlled livestock grazing. Development of these areas might also include livestock management improvements such as fencing and stock watering facilities.

Siting of barrier structures would be critical to maximize their effectiveness. Thorough understanding of geomorphic processes would be of utmost importance in selection of appropriate sites. Improperly sited structures would be less effective and could actually be detrimental in some circumstances. Likewise, structure design and maintenance would be of great importance.

Sediment barrier structures of this type were proposed by the Soil Conservation Service (SCS) in 1941 [Department of Agriculture, 1941]. SCS proposed five sediment barrier structures which would have been rolled earth embankments with reinforced concrete spillways. These structures would have been built to an elevation about 10 to 15 feet above the terrace level on either side of the Rio Puerco arroyo with training dikes extending to either side.

The Bureau of Land Management (BLM) and the SCS have successfully regraded and stabilized reaches of the San Simon River and its tributaries in southeastern Arizona using sediment barrier structures. Conditions on the San Simon and the history of arroyo formation are in many ways similar to the Rio Puerco.

Two relatively large structures have been built on the main stem of the San Simon to retain sediment and regrade the channel. These structures are low (10-15 feet high) dikes extending across the river terraces with concrete drop structures on the main channel. Crest elevations of the spillways are approximately at the terrace level. The older structure has a pipe drop inlet for low flows. The first of these structures was built in 1953 and the most recent was built in 1980. Each of these structures has caused the gully of the San Simon Arroyo to be completely filled for some distance upstream and continuation of the channel filling process is evident for several miles above the structures. Floodplains and stable riparian areas have become established in these reaches. Regraded reaches of the San Simon provide multiple benefits including increased livestock forage, wildlife habitat, recreational opportunities, and flood reduction.

The San Luis Diversion Dam was a log structure similar to the proposed barriers. Bryan and Post [1927] reported that the diversion dam at San Luis "vastly decreased" erosion for 10,000 feet above the dam and an arroyo 150 feet above the dam filled from "at least 20 feet" deep to 3 feet deep after the dam was built. The San Luis Dam was destroyed in a large flood in 1951.

The effectiveness of this approach to reducing the sediment load of the Rio Puerco at Bernardo cannot be predicted with the certainty that applies to the large dam alternative. These structures would not immediately reduce the sediment load at Bernardo to the degree that could be expected from a dam impounding water on the lower reach of the Rio Puerco. Sediment transport mechanics in the Rio Puerco are unknown and the downstream effect of sediment control high in the basin cannot be evaluated without detailed modeling analysis.

Due largely to natural causes, the average sediment load of the Rio Puerco has been reduced by some 50 percent compared to the late 1960s and early '70s. Reduction from late 19th and early 20th century loads is about 80 percent. By working with the continuing geomorphic evolution processes of the basin, this alternative offers a potential long term solution to the sediment problem. Modeling of the basin would provide a better estimate

of sediment reduction under various alternatives, but would require effort well beyond the scope of the present investigation.

Barrier structures would not cause inundation of large areas outside the active arroyo, so cultural resource impacts could probably be largely avoided. A net benefit to wildlife would be possible if stable riparian areas were created upstream of the structures.

The cost of barrier structures would be moderate to high depending on siting and the number of structures built. The San Simon Barrier Structure on the San Simon River in Arizona cost about $1,300,000 in 1980 and the proposed Timber Draw Structure on the same river is currently estimated to cost $2,000,000. Rio Puerco structures would be somewhat larger and would probably cost $3,000,000 to $5,000,000 each. Five or ten structures might be required to maximize their effectiveness.

Alternative C: Arroyo Grade Control Structures

These structures would be designed to enhance natural arroyo evolution processes by flattening the slope of the Rio Puerco and inducing floodplain building and deposition in selected areas. Bryan and Post proposed low brush and rock check dams or weirs about 10 feet high in the main channel and bottom of the arroyo as a means to regrade the Rio Puerco [Bryan and Post, 1927]. Bryan envisioned 80 of these structures spaced every few miles along the main channel of the Rio Puerco and 138 structures in tributary arroyos. The 1941 Soil Conservation Service plan also included weirs of this type. Because of the large number of structures and extensive maintenance required, effective sediment control by this method would require a long term project commitment.

As with the barrier structures (Alternative B) proper siting of these structures to take advantage of continuing natural processes would be critical to their effectiveness. Maintenance would be a particular concern with smaller structures. There would be a possibility of the structures being damaged or destroyed by large floods. Careful engineering would be needed to minimize the risks of structures being washed out. New technologies such as inflatable dams could be investigated as a means of causing low flows to spread over banks while allowing higher flows to run in the channel.

Activities limited to active arroyo channels would probably cause minimal disturbances to cultural resources. Grade control structures could provide a net benefit to wildlife if they promote the development of stable riparian areas.

These structures could be of relatively simple design and could be built by local labor. The estimated cost of individual structures would be on the order of $100,000 to $250,000 depending on site and design.

Alternative D: Watershed Management

This alternative assumes that changed land use and management practices can contribute to an appreciable reduction of sediment load at Bernardo. It should be recognized that sediment production from the Rio Puerco basin would probably be high regardless of land use and management practices and that some areas can be expected to contribute more sediment than others. The purpose of land use and land management changes would be to reduce sediment production in the basin by increasing plant cover or vegetation type on the range, or to create other conditions more conducive to rainfall interception and infiltration.

The prevalent land use in the Rio Puerco Basin is livestock grazing. Local economies in the Rio Puerco Basin depend heavily on the ranching industry. Social and economic impacts of land use and land management changes on these communities would need to be carefully assessed. To some degree the costs of increased sediment production due to land use might be regarded as acceptable in maintaining a viable rural economy.

Implementation of watershed management and land treatment might include reduction of range stocking levels, changes in grazing management such as increasing use of rest-rotation or seasonal deferred grazing, excluding or limiting grazing in selected areas, ripping, pitting, contour furrowing, constructing gully control structures, seeding, and brush control. Changes in land management may require livestock improvements such as fencing or water distribution systems.

The diversity of soil types, vegetative communities, climatic conditions, and terrain are also factors to be considered in this context. Site specific watershed management and land treatment plans would need to be developed for individual range management units. Concentration of watershed treatment efforts in riparian areas to enhance the sediment trapping effects of floodplain building would probably produce the greatest sediment control effect on a per acre basis.

The size of the Rio Puerco basin and the diversity of land ownership and land use practices present formidable obstacles to implementing this approach. To be effective a large area of the basin would have to be included. Extensive continuous cooperation among land owners, agencies, and Indian tribes would be needed. Management practices on private lands are the prerogative of the owner and would be difficult to coordinate.

The Corps [1985] estimated that sediment reduction of 33 percent could be realized by implementing watershed treatment. However, the effectiveness of watershed improvements for reducing sediment load at Bernardo cannot be estimated with any confidence. There is not adequate up-to-date information to determine the contributions of the various sources of sediment. For example, changes in stock grazing practices may reduce sheet and rill erosion in the basin, but if the main source of sediments is bank

erosion and widening of the main arroyo channel, changing stock management practices will not significantly affect the sediment load downstream. In addition, the mechanics of sediment transport through the system are not well understood. It is unclear how an incremental reduction in erosion high in the basin contributes to reduction of sediment at the mouth. The relationship is not necessarily one-to-one because sediments may be deposited along the way.

Individual watershed improvement projects would probably have to be justified on the basis of onsite benefits unless the links to downstream damages can be more definitely quantified.

Structures to reduce or control headcutting gullies in the upper watershed require proper siting and maintenance to be effective. Structures that are improperly sited, poorly designed, or inadequately maintained may actually contribute to the sediment problem.

Watershed improvements could involve disturbances over a wide area and cumulative impacts to cultural resources could be significant. Watershed improvements would be generally beneficial to wildlife.

Cost of watershed treatment would be moderate to high. The Corps estimated cost ranging from $24,650,000 to $88,390,000 in their 1985 plan.

Alternative E: Sediment Management on the Rio Grande and Elephant Butte Reservoir

Under this alternative, management and structural changes on the Rio Grande and at Elephant Butte Reservoir would be instituted to reduce deposition in channels and in the active pool of the reservoir. The purpose of this alternative is to select the locations where sediments would be deposited and to manage the river-reservoir system accordingly. This alternative could encompass, but would not be limited to, mechanical dredging in the river, reservoir, or in other channels.

The essence of this alternative is the routing of sediment to controlled settling basins either by mechanical dredging or by means of dikes, channels, and other water control structures. After settlement of sediment, clearer water would then be delivered back to the river or reservoir. Selection of appropriate settling basin areas and the management of these areas would be major considerations in this approach. Improperly managed dredging could create severe environmental impacts. However, dredging impacts can be mitigated in a number of ways. Routing sediment to settling basins by non-mechanical means would eliminate some of the problems that can accompany dredging.

A large area at the head of the original reservoir has already been completely filled with sediment to a level above the spillway crest elevation and might provide a suitable zone

for settling basins. This area extends approximately 10 miles north to south from San Marcial to Milligan Gulch, and is 1/2 to 1 mile wide. The river channel is confined to the eastern side of this floodplain by the levee that protects the Low Flow Conveyance Channel. Since the Conveyance Channel was constructed in the 1950's, all floodplain deposition above the reservoir has occurred east of the levee and the river and narrow strip of the floodplain are now perched as much as 10 feet above the floodplain to the west of the levee.

The continuing confinement of the river to the narrow strip east of the levee has notable adverse consequences. The aggradation of the river channel and floodplain strip east of the levee increases the chances that the levee will be overtopped and the Low Flow Conveyance Channel severely damaged. Aggradation of the river upstream from the reservoir may be aggravated by the situation posing an increasing threat to the Bosque del Apache National Wildlife Refuge and other facilities. Using the floodplain area west of the levee as a sediment deposition area would mimic, in many ways, the natural process of floodplain building that has been artificially interrupted by the levee.

Development of the reservoir area between San Marcial and the head of the reservoir pool for settling basins would require changes to the Low Flow Conveyance Channel. A re-routed Conveyance Channel could be incorporated into the system to convey water discharged from the basins to the reservoir. A plan to re-route the Conveyance Channel could encounter formidable institutional obstacles.

Significant opportunities exist for mitigating potential environmental impacts that could occur under this alternative. Settling basins would contain relatively shallow, slowly moving water. Sedimentation in the basins would create delta environments that might be protected, to some degree, from the rising and falling of the reservoir. Controlled sediment deposition could also provide some opportunities for salt cedar control.

Dredged material could be used to build islands in the shallow upper end of the reservoir which would provide excellent habitat for birds. Raising sediment above the water level to build islands would require mechanical dredging. During periods of low reservoir levels, islands would become hills in the floodplain.

Reclamation is continuing to evaluate and study the San Marcial reach of the Rio Grande and headwaters of Elephant Butte Reservoir in order to develop appropriate management strategies.

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APPENDIX B: ECONOMICS OF EROSION AND SEDIMENT CONTROL

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Introduction

The primary economic damages from erosion in the Rio Puerco basin and subsequent deposition of the sediment are due to lost productivity of rangeland in the basin, reduced water supply due to depletion of storage capacity and increased evaporation losses in Elephant Butte Reservoir, reduced recreational opportunities at Elephant Butte Reservoir, increased maintenance costs of water conveyance facilities and other infrastructure, increased flood damages, and adverse impacts on non-use values.

This appendix presents some rough general estimates of the costs of erosion from the Rio Puerco Basin and the subsequent downstream deposition. These estimates have been developed from existing information, previous investigations, and from regional and national studies. Typical methodologies for estimating benefits from improved water quality have included: measuring replacement or repair costs actually incurred, measuring the willingness to pay to avoid the adverse impacts from poor water quality, measuring the willingness to pay for better water quality, estimating the cost of replacing damaged facilities, and the cost of providing alternate sources of water.
This appendix is not intended to provide definitive estimates of project costs, benefits, or economic justification for sediment control projects. The analysis required to provide such estimates is well beyond the scope of this preliminary study. A significant effort to compile up-to-date site specific data would be needed to refine these estimates and to reduce uncertainties inherent in the methods used to develop them.

A distinction is made between damages due to erosion and deposition of sediments, and potential benefits that could be realized through a sediment control project. Damages are the costs imposed on society in a variety of ways by the sediment. Benefits are cost savings that might be realized by implementing a program to reduce erosion or sedimentation. As a practical matter, erosion and sedimentation cannot be reduced to zero, so benefits will always be less than damages. Benefits would vary depending on the type of sediment control project or program. For example, a dam on the lower Rio Puerco would create no rangeland productivity benefit in the upper basin.

Damages associated with soil erosion and sediment deposition include onsite and offsite damages. Onsite damages are primarily productivity related damages that are reflected by lower crop yields on cultivated land, reduced forage production on rangeland, and reduced acreage available for production due to gullying or extreme reductions in fertility that make land unsuitable for crop production or grazing.

Offsite damages occur as a result of sediment impairing water related activities or values downstream from the site where soil erosion takes place. Damages to the Rio Grande and Elephant Butte Reservoir caused by sediment originating in the Rio Puerco basin are offsite damages.

Offsite damages can be further divided into instream and offstream impacts [Clark, et. a., 1985]. Instream impacts include biological effects, recreation, water storage reduction, and impairment of navigation. Offstream impacts include flood damages, damage to water conveyance and storage facilities, and increased water treatment needs.

Offsite soil erosion damages are difficult to quantify in general because of the dispersed nature of sediment sources and imperfect knowledge of the links between sediment and water related behavior. Previous studies have generally assumed that damages are proportional to the amount of eroded soil, concentration of sediment, or to the amount of sediment delivered.

Most estimates of erosion damages and potential benefits assume that each ton of sediment contributes equally to overall damages. However, it must be recognized that this is a simplistic assumption because sediment damage thresholds may exist, below which damages may be very small. Damages caused by the first ton eroded or first acre foot deposited in the reservoir are negligible. Later, incremental damages become increasingly severe.

There are costs associated with both non-structural and structural solutions to soil erosion problems. Non-structural solutions may involve some land being taken out of production, which could reduce total agricultural output in the short run. Fencing, water distribution systems, and inputs needed to reseed areas or break up hard packed soil increase the cost of grazing land. Construction alternatives require capital investments to build, operate, and maintain sediment control structures.

The majority of previous studies of the economics of erosion have looked at the on-site productivity related damages from soil erosion [Alt, Osborn, and Colacicco, 1989; Pierce, et. al., 1983; Pierce, et. al., 1984; Wade and Heady, 1978; Larson, et. al., 1983; Phipps, Crosson, and Price, 1986]. However, in the case of the Rio Puerco basin, the majority of soil erosion damages may be off-site damages due to the relatively low level of agricultural production in the basin and the high level of water use downstream

A few studies have been done to measure the offsite damages from soil erosion. A book by Clark, Haverkamp, and Chapman [1985] provides a detailed discussion of the impacts of sediment and sediment related chemicals as well as estimates from a variety of sources of the economic impacts of soil erosion in the United States. The total damages from soil erosion in the United States were estimated to range from $3.2 billion to $13.0 billion annually with a best estimate of $6.1 billion. The largest single damage category was recreation, which accounted for about one-third of the total damages. Although the estimates were subject to a large amount of uncertainty, they provide important information on the magnitude of offsite costs and a methodology for estimating offsite erosion damages.

A later study by Marc Ribaudo estimated the off-site costs of soil erosion and the offsite benefits from the Conservation Reserve Program (CRP) by geographic regions of the United States [Ribaudo, Feb. 1989]. The CRP is a federal land set aside program designed to take highly erodible land out of production. Farmers are paid a yearly rental payment plus 50 percent of the cost of establishing permanent vegetative cover for a contract period of 10 years. The intent of the program is to reduce soil erosion and the associated damages.

Ribaudo presented estimates of the total off-site damages due to soil erosion from all sources and the reduction in damages likely to result from CRP. Ribaudo's best estimate of total offsite damages from soil erosion in the United States was about $8.8 billion annually, which translates into a value of $1.78 per ton of eroded soil. The best estimate of offsite damages in the mountain region; which includes New Mexico, Idaho, Montana, Wyoming, Nevada, Utah, Colorado, and Arizona, was $871 million annually or $1.12 per ton. The best estimate of the offsite benefits from CRP was $3.7 billion annually for the entire United States and $477 million annually for the mountain region. Other studies have been completed using the same methodology to estimate the off-site benefits from reducing soil erosion [Ribaudo and Young, 1989; Ribaudo, 1989].

Lost Land Productivity in the Rio Puerco Basin

Soil erosion in the Rio Puerco Basin results in reduced forage growth and reduced acreage suitable for grazing. This represents an onsite cost of erosion in terms of reduced feed and livestock production, lost rental revenues, and increased costs of alternative livestock feed. To measure these costs it is necessary to estimate the loss of forage due to erosion and the value of that forage and attendant reduced livestock production.

A 1985 Corps of Engineers study for the Rio Puerco and Rio Salado Basins estimated the productivity benefits from improved range management practices [Corps of Engineers, 1985]. The range management scenarios evaluated included implementation of existing grazing management systems, implementing grazing management on all critical acres in the two basins, and a scenario with grazing management systems plus gully stabilization structures. The first scenario includes treatment of 1,012,000 acres while the second and third scenarios treat 2,771,000 acres.

Private and public benefits were estimated for each scenario. The benefit categories in the analysis related to improving rangeland conditions included the value of increased forage and the value of supplemental livestock feeding. Productivity benefits were estimated by using an average increase in forage production in the area from improved range management and multiplying the increase times the number of acres treated. The total increase in forage was then multiplied by the value of that forage.

The same procedures are used in the present analysis to estimate the value of productivity losses from soil erosion in the Rio Puerco Basin. Prices are updated to the most current available. It should be noted that the productivity benefits will not occur for alternatives where sediment control structures are used which trap sediment after it is moved off of the field or range. Soil fertility will still be adversely affected if sediment control structures are built downstream from erosion sites.

The Corps of Engineers study estimated an average annual increase in forage of 60 pounds per acre if soil erosion controls were implemented. Assuming one animal unit month (AUM) equals 750 pounds of forage, erosion results in an estimated loss of .08168 AUM per acre per year.

There are approximately 2.25 million critical acres in the Rio Puerco watershed [Corps of Engineers, 1985]. Based on the above estimates, soil erosion reduces potential forage production by 183,780 AUM. In 1993 the average private grazing fee rate for rangeland in New Mexico was $7.55 per AUM [National Agricultural Statistics Service, 1993]. Therefore, the estimated forage damages from soil erosion are estimated to be about $1.39 million annually.

The Corps of Engineers also estimated some benefits from decreased death losses and potential supplemental feeding as a result of controlling soil erosion. The value used in their study was $3.92 per acre over a 100 year period. Better information is not readily available to estimate these damages. Therefore, the value is rounded to $4.00 per acre and is discounted at the current federal water project rate of 8.0 percent to obtain an annual value of $0.32 per acre. This cost is applied to the total critical erosion acres, resulting in estimated death rate and supplemental feeding damages of $720,000 annually.

Reduced Storage Capacity of Elephant Butte Reservoir

Several methods can be used to estimate the value of lost reservoir storage capacity including the cost of dredging, cost of increasing reservoir size to maintain available storage, cost of building new storage facilities, and the cost of preventing sediment from reaching the reservoir. Crowder [1989] used these methods to estimate reservoir sedimentation damages in each region of the United States.

The first three methods are based on the cost of replacing usable storage or reversing damages caused by deposited sediment. The fourth method is based on actions taken to avert damages and assumes that the cost of reducing erosion equals the benefits from the program. This method is not appropriate for analyzing benefits from reducing erosion in the Rio Puerco basin. These methods do not necessarily reflect alternatives that are feasible. For example, building a new dam to replace lost storage capacity may not be technically feasible or environmentally acceptable.

Sediment deposited in Elephant Butte Reservoir attributable to the Rio Puerco Basin is estimated to be about 60 percent of the annual 3,200 acre-feet per year deposition, or about 1,900 acre-feet per year. Based on a cost of $1.90 per cubic yard of sediment removed, the cost of removing 1,900 acre-feet of sediment each year would be about $5.9 million annually. (1,900 acre feet = 3.06 million cubic yards)

The reservoir sedimentation costs estimated by Ribaudo [1989] for the Mountain Region were $0.157 per ton of eroded soil for damages and $0.184 per ton for benefits estimated for the CRP. Assuming about 3 million tons of soil erosion in the Rio Puerco basin annually, reservoir sedimentation damages according to this estimate would be between $431,750 to $506,000 annually. Updating the damages to 1993 using the gross domestic product (GDP) deflator results in a range of costs from $490,400 to $574,700 annually. The relative proximity of Elephant Butte Reservoir to the Rio Puerco could be a factor in the relatively low cost values generated using Ribaudo's estimates.

An alternative method for estimating damages due to reservoir sedimentation uses the additional construction cost needed to accommodate anticipated sediment deposits as a measure of the costs imposed by eroded sediment. This method is not easily applied because the amount of extra capacity needed is based on current conditions as perceived by water managers. If the extra capacity built is not sufficient, then damages would be underestimated. If the extra capacity is never used, then damages would be overestimated. On a site-by-site basis the amount of extra capacity constructed could be adjusted to reflect the true construction costs imposed by sediment. However, averting behavior does not reflect perfect foresight and adjusting costs may not reflect the true costs imposed on society.

The methods of estimating damages due to reservoir sedimentation that are described above are not entirely satisfactory. These methods assume that depleted water storage capacity can be replaced or restored. In the case of Elephant Butte Reservoir, replacement or restoration of depleted storage is probably not feasible. Damage due to reservoir sedimentation is a function of the effect that sediment deposition has on the water supply downstream from the reservoir, and the economic benefit of the water as determined by its end uses. The net effects of sediment on the water supply could be estimated by applying a mathematical model to simulate future reservoir operations. A rough model of this type developed for and applied to Elephant Butte Reservoir is described in Appendix G. Evaluating the economic benefit of water as determined by its end uses would require detailed and extensive economic analysis that is beyond the scope of the present investigation.

The Corps of Engineers [1985] derived values for the economic benefit of water in the Middle Rio Grande Valley. These values were $31.47 per acre foot for agricultural water and $364.66 per acre foot for municipal and industrial water. A weighted average of $146.99 per acre foot was given for all uses. This value updated to 1993 dollars is

approximately $193 per acre foot. Assuming that downstream water shortages due to sedimentation amount to 200,000 acre feet in the next 100 years, average damages would equal about $386,000 per year.

Reduced Recreational Opportunities at Elephant Butte Reservoir

The primary impacts of reservoir sedimentation on recreation would be expected to be imposed on fishing, boating, and possibly swimming. The primary recreational uses of Elephant Butte Reservoir include boating, fishing from shore and by boat, swimming, water-skiing, picnicking, camping, and hiking.

Elephant Butte Lake State Park is the largest state park in New Mexico. Facilities at the park include: over 200 developed campsites, 100 electrical hook-ups for recreational vehicles, comfort stations with showers, dump stations, boat ramps, and concession-run marinas. Total visitation to the park has averaged about 1,466,100 user days from 1975 to 1993. Over the last three years visitation has averaged about 1,752,200 user days per year and park revenues have averaged about $557,500 per year.

Based on information provided by the Park, over 50 percent of total use is attributable to boating and fishing from boats. Other primary uses of the reservoir include: swimming, fishing from shore, picnicking, and hiking. These activities are not mutually exclusive. Many people participate in more than one type of recreational activity during a visit to the reservoir, complicating attempts to determine the level of different uses. The types of recreation at Elephant Butte Reservoir appear susceptible to impacts from soil erosion.

Recreation damages from sedimentation are the result of reduced recreational opportunities or reduced benefits from a recreational outing. The damages are equal to the benefits foregone from not being able to participate in an activity or from reduced benefits from a poorer quality recreational experience. To measure recreation damages accurately, information is needed on the types of recreation affected downstream from the source of soil erosion, the value of that recreation, and the impact of sediment on each type of recreation.

Estimating these damages is difficult due to the number of linkages that must be accounted for between erosion taking place and recreational impacts occurring. For example, eroded soil carried down a waterway and deposited in a stream or reservoir may not have any effect on fish catch or available recreation areas until a threshold level of deposition is attained. Up to that threshold recreational damages may be zero. Similarly, turbidity may not affect fish activity or aesthetics until a threshold level is attained.

Recreational fishing damages from sediment can be estimated using the RIOFISH model developed by the New Mexico Water Resources Institute [New Mexico Water Resources Institute, 1990]. RIOFISH is a simulation model that can analyze the impact of changes

in water quality or other site quality factors on recreational fishing use and benefits. For this analysis the RIOFISH model is first run to determine a baseline level of recreational use and benefits. The model is then run a second time changing the parameters for lake area, water quality, and fish catch rate to estimate changes in recreational fishing benefits due to sediment related impacts.

Due to the lack of data available to estimate non-fishing recreational damages at Elephant Butte Reservoir, these damages are assumed to be proportional to the lake volume lost due to sedimentation. Annual non-fishing recreational damages from sediment are estimated to equal the annual contribution of the Rio Puerco to sedimentation of the reservoir divided by the total capacity of the reservoir. The total value of recreation affected by sediment is multiplied by this factor.

This method is not likely to be realistic throughout the range of reservoir sedimentation. For example, recreation may not be affected by the first ton of deposited sediment and lake use could fall to zero before the lake became completely filled with sediment. However, due to the lack of information a linear sediment-use relationship is used. All recreational impacts due to sediment from the Rio Puerco Basin are assumed to occur at Elephant Butte Reservoir, though it is recognized that some recreation occurs upstream of the reservoir.

Total recreational use of Elephant Butte Reservoir has averaged about 1,752,200 user days annually over the last three years. Based on the RIOFISH simulation model, angler use may have accounted for about 386,500 days of use. Based on information provided by Elephant Butte State Park and the RIOFISH model, about 1,095,000 user days are attributable to boating, 386,500 user days are attributable to fishing, and about 219,000 user days are attributable each to swimming, picnicking, and to hiking.

The RIOFISH model was run using a 1 percent reduction in shoreline, a 1 percent reduction in fish catch rate, and a .02 of one percent reduction in surface area for a one year period. These percentage change in shoreline and catch rate was chosen to represent a small decrease in water quality and available fishing facilities that could result from erosion. Based on these changes the RIOFISH did not indicate a decrease in user days, but benefits did decrease as a result of a degraded fishing experience. The loss in benefits were estimated to be about $376,000 annually.

Two sources of data can be easily applied to use of Elephant Butte Reservoir to estimate the value of boating and swimming. The first is the unit day method, where the value is based on a point system from zero to 100 points for different activity categories. The higher the number of points, the more unique and valuable the recreational activity is. The unit day value for Elephant Butte is $6.29 per day in 1993 dollars based on the general recreation category and a point value of 80 points [U.S. Water Resources Council, 1983]. Motorized boating and swimming would fit into the general recreation category. The

second method is based on general recreation values estimated for the New Mexico and Arizona region by the Forest Service [USDA Forest Service, 1990]. The average value estimated by the Forest Service was $6.90, or $8.98 per activity day in 1993 dollars. The Forest Service estimates are used because the represent estimates more specific to the region and are based on study results. Total damages for all three categories of recreation affected by sediment at Elephant Butte Reservoir are presented in Table B-1.

Table B-1: Estimated recreational damages from sediment

Activity	Estimated Use (Days)	Benefit per User Day	Total Damages
Boating	1,095,125	$8.98	$24,800
Fishing	386,500	---	$376,300
Swimming	219,025	$8.98	$5,000

Recreation costs estimated by Ribaudo for the Mountain Region were $0.300 per ton of eroded soil for damages and $0.066 per ton for benefits estimated for the CRP. Applying these values to the Rio Puerco result in damages from $198,000 to $900,000 annually. Damages in 1993 dollars range from $224,900 to $1.02 million annually. The estimated damages using RIOFISH and the loss in storage percentages are at the low end of the range using the regional estimates.

Damages to Water Conveyance Facilities and Other Infrastructure

The Corps of Engineers [1985] estimated that ditch and canal maintenance costs for the Socorro Main Canal and the Low Flow Conveyance Channel due to sediment from the Rio Puerco and Rio Salado watersheds amounted to about $800,000 annually. The Corps attributed approximately five-sixths of these damages to sand coming from the Rio Salado. The silt and clay sediment load of the Rio Puerco may not be a major direct contributor to channel sedimentation above the reservoir.

The Corps of Engineers used a sediment removal cost of $1.40 per cubic yard to estimate channel cleaning costs. Updating the sediment removal cost to $1.90 per cubic yard results in damage estimates of $1.086 million annually. Probably less than 20 percent of the sediment deposited upstream of the reservoir comes from the Rio Puerco. The cost of removing Rio Puerco sediments from active channels above the reservoir is on the order of $217,000 annually.

Extraordinary maintenance is needed to open channels into Elephant Butte Reservoir during times of falling reservoir levels. Most sediments from the Rio Puerco are deposited

in the reservoir and represent a significant portion of the material that must be excavated to open channels to the reservoir. Channel excavation in 1991 to open 3 miles of channel between Rangeline 26 and Rangeline 30 cost approximately $800,000. The incremental effect of reducing sediment from the Rio Puerco on these costs cannot be estimated.

This category of costs also includes damages related to repair and replacement of roads, bridges, utilities, and railroad lines. Past flood events have resulted in the need to move railroad lines and roads, the abandonment of the town of San Marcial, and damage to several bridges. In June 1991, failure of the railway embankment at San Marcial caused by high water directly related to sediment deposition in the Rio Grande Floodway caused approximately $1 million in damages.

In a court case filed against the United States [U.S. Court of Claims 90-54, 1960], The Atchison, Topeka, and Santa Fe Railway Company (AT&SF) claimed that the cost of raising a bridge and track approaches and relocating a rail line threatened by sediment deposition and flooding was $8.0 million in 1960 dollars. This cost is $38.8 million adjusted to first quarter 1993 levels. In 1929 floods and deposited sediment resulted in the removal of AT&SF Railway Company shops and extensive damage to transportation facilities. Total property damages estimated for the 1929 floods were about $1.8 million at the time of the floods. Although damages imposed on the railroad facilities due to sediment cannot be disaggregated from the damage estimates for the 1929 floods, the damages due to sediment are likely to have been at least as large as the costs indicated in the 1960 court case. Therefore, as a rough approximation, the costs imposed by sediment on the railroad may be $38.8 million every 50 years or about $776,000 annually. This translates into a present value of about $9.5 million over a 50 year period. Although these damages are fairly infrequent, the high relative cost of moving railroad tracks and modifying bridges results in substantial annual damages. The contribution of the Rio Puerco to these damages is unknown but may be relatively minor due to the nature of the sediment coming from that source.

In addition to these costs, sediment creates problems for irrigators using Rio Grande water. High levels of sediment reduce the infiltration of water into the soil and increases the need for ditch maintenance. These costs cannot be estimated reliably for irrigators in the area due to the diffuse nature of the damages and incomplete information on maintenance time directly attributable to deposited sediment.

The costs of ditch and conveyance system damages estimated by Ribaudo for the Mountain Region were $0.094 per ton of eroded soil for damages and $0.083 per ton for benefits estimated for the CRP. Applying these values to the Rio Puerco result in damages from $249,000 to $282,000 annually or $282,800 to $320,300 in 1993 dollars.

Flood Damages

Sediment from soil erosion can contribute to flood damages in several ways. Deposited sediment can raise the stream bed, reducing the flood carrying capacity of a stream and reducing the flow needed before flooding begins. Suspended sediment increases the volume of water, which increases the potential for flooding. Sediment deposited during a flood event also increases the cost of cleaning up after a flood.

Runoff and sediment from the Rio Puerco Basin has contributed to several flood events [Corps of Engineers; April, 1985]. Damages from these floods have included damages to homes and personal belongings, public buildings, commercial establishments, transportation and water conveyance infrastructure, farmland, and crops. In 1929 the town of San Marcial was covered by several feet of sediment during a flood, causing the town to be abandoned [Corps of Engineers; April, 1985].

It is assumed for purposes of this study that a levee system between San Acacia and Elephant Butte Reservoir will effectively prevent flood damages along that reach of the Rio Grande in the future.

Non-use values

This category of values includes existence or intrinsic value and bequest values of a resource. Existence or intrinsic value is the value people receive from simply knowing that a resource or unique feature exists. For example, some people may derive some benefit from knowing Elephant Butte Reservoir exists and is not threatened by high levels of sediment. People can have a positive existence value even though they may not plan on making a trip to the Reservoir. Bequest values are the benefit people derive from knowing a resource will be protected so their descendants can use the resource if they so desire.

Non-use values can be derived from local, state, national, or even global populations if the resource is well known and very unique. In the case of Elephant Butte Reservoir and the Rio Grande River, non-use benefits are likely to accrue mostly to local or state populations. Measurement of non-use values is difficult due to the widely dispersed population potentially affected. However, due to the large number of people who could potentially place some non-use value on Elephant Butte Reservoir, non-use benefits are potentially large. Non-use value benefits from reduced soil erosion in the Rio Puerco are not estimated in this analysis.

Previous methods used to estimate non-use values have generally relied on some type of contingent valuation survey. In these surveys people are asked questions related to a site or resource through mail questionnaires, telephone interviews, or personal interviews. The respondents may be chosen to represent a sample of non-users. A second technique is

to ask respondents to assume that they will not use the resource. Another survey technique is to associate certain responses with non-users and use only those willingness to pay responses in estimating non-use value. Lastly, a non-use question could be asked without specifically being told to assume zero use.

Non-use values estimated for other resources cannot be applied to Elephant Butte Reservoir because each resource is unique and not likely to have similar non-use values. Therefore, non-use values are not estimated in this analysis.

Summary

Damage estimates from sediment originating in the Rio Puerco basin are presented in Table B-2. Sediment-damage relationships in the Rio Puerco - Rio Grande area are subject to considerable uncertainty and the damage estimates are based on many simplifying assumptions. These are preliminary estimates and should be regarded with caution. Damages calculated using Ribaudo's [1989] regional estimates are based on 3,000,000 tons of annual erosion and are expressed in 1993 dollars using the GDP deflator.

It must be emphasized that these estimates represent the economic damages imposed by Rio Puerco sediments and not the benefits from reducing soil erosion. Erosion is a natural process that occurs regardless of the actions taken to reduce sediment and, therefore, sediment related damages will never be reduced to zero except at great cost.

An example can be used to clarify the distinction between damages and benefits. The Corps of Engineers estimated erosion damages at an annual cost of $5.65 million, or $7.65 million in 1993 dollars [Corps of Engineers, 1985]. They estimated that soil erosion in the Rio Puerco Basin could be reduced by about one-third by implementation of grazing and land management improvements. Assuming a proportional reduction in damages, the sediment related benefits from improved range management would be one third of $7.65 million, or $2.55 million. This example is simplistic, but it does illustrate a potential use of soil erosion damage information.

The reader will note wide ranges and significant discrepancies in the damage costs presented in Table B-2. It must be understood that these are rough approximations of very complex analyses and necessarily reflect considerable uncertainties and broad assumptions.

Table B-2: Preliminary estimated annual damages due to soil erosion in the Rio Puerco Basin

Damage Category	Estimated Annual Damages (Millions)	Regional Annual Damage Estimates per Ribaudo [1989] (Millions)
Productivity	$2.11	--
Reservoir Sedimentation	$0.39 - $5.90	$0.49 - $0.57
Recreation	$0.42	$0.22 - $1.02
Canal Maintenance	$0.22	$0.28 - $0.32
Infrastructure	$0.78	--
TOTAL	$3.92 - $9.43	$0.99 - $1.91

The wide range of damages shown in Table B-2 indicates the large amount of uncertainty involved in estimating off-site soil erosion damages. The greatest range of costs occurs for the reservoir sedimentation damage category. The low estimate is based on an estimated value for water while the high cost is based on the cost of reversing sediment deposition. The high estimate does not measure actual damages incurred and is likely to over-estimate sedimentation damages. However, the low estimate does not include all potential lost reservoir uses associated with sedimentation. The actual value is likely to be somewhere within the range.

The estimates taken from the Ribaudo study are based on average damages over a large region and, therefore, do not consider local conditions. The relatively high sediment load in the Rio Puerco may result in greater damages than would be estimated using the numbers from the Ribaudo study.

The relatively small damages from soil erosion are the result of the small percentage losses in water use that can be attributed to sediment. Other factors, such as seasonal and year to year fluctuations in the elevation of Elephant Butte Reservoir, currently have more effect on water use than sediment. At some point in the future a threshold may be reached where sedimentation could have a large impact on water supply in the area.

The estimates presented above include several damage categories. However, there are potentially some benefits from soil erosion that would be reduced if sediment levels decreased. Deposited sediment could create a habitat for aquatic life that may not exist

otherwise. Loss of this habitat could result in recreational, biological, and other use and non-use damages.

A major problem in estimating damages from soil erosion is the assumption that damages are proportional to the amount of soil eroded. Very little is actually known about the fate of soil after it is washed off of the land. [Phipps, et. al., 1986]. Some eroded soil is captured by reservoirs, but that most of it is distributed on slopes, flood plains, and other portion of stream valleys. A large part of eroded soil is deposited near the source of erosion and it may take several months or even years for sediment to move downstream where it can affect human activity and create damages. Therefore, eroded soil as measured at the site of origin may not accurately reflect the amount of damages imposed by sediment downstream.

General cost estimates were used in the analysis to estimate the costs of cleaning up sediment related damages. These costs need to be better estimated and some account must be taken of non-monetary costs that may be imposed in addition to the simple cost of cleaning. Non-use values in terms of option and bequest values should also be taken into account in estimating damages. These values could be related to recreational activities or potentially animal and insect species that may be dependent on the existence of the reservoir.

Refining the estimates of economic impacts due to erosion and sedimentation in the Rio Puerco - Rio Grande system would require extensive site specific studies. In order to narrow the range of estimated soil erosion damages from the Rio Puerco, extensive studies would need to be done to track the origin of sediment causing economic damages and to estimate the portion of damages attributable to this sediment. Sediment studies defining the source of sediment affecting various water related uses are needed to link erosion by area with damages by type of use. Site specific studies would also be needed which could be used to model recreation related responses to turbidity and deposited sediment. The RIOFISH model provides a useful tool for translating water quality changes into changes in angler benefits, but no such tool exists for other types of recreation in the area. Contingent valuation type studies would be needed to estimate non-use values for Elephant Butte Reservoir.

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APPENDIX C:HIGHLIGHTS OF GEOLOGIC HISTORY AND ITS IMPACT ON SEDIMENT AND CONTAMINANT PRODUCTION IN THE RIO PUERCO BASIN

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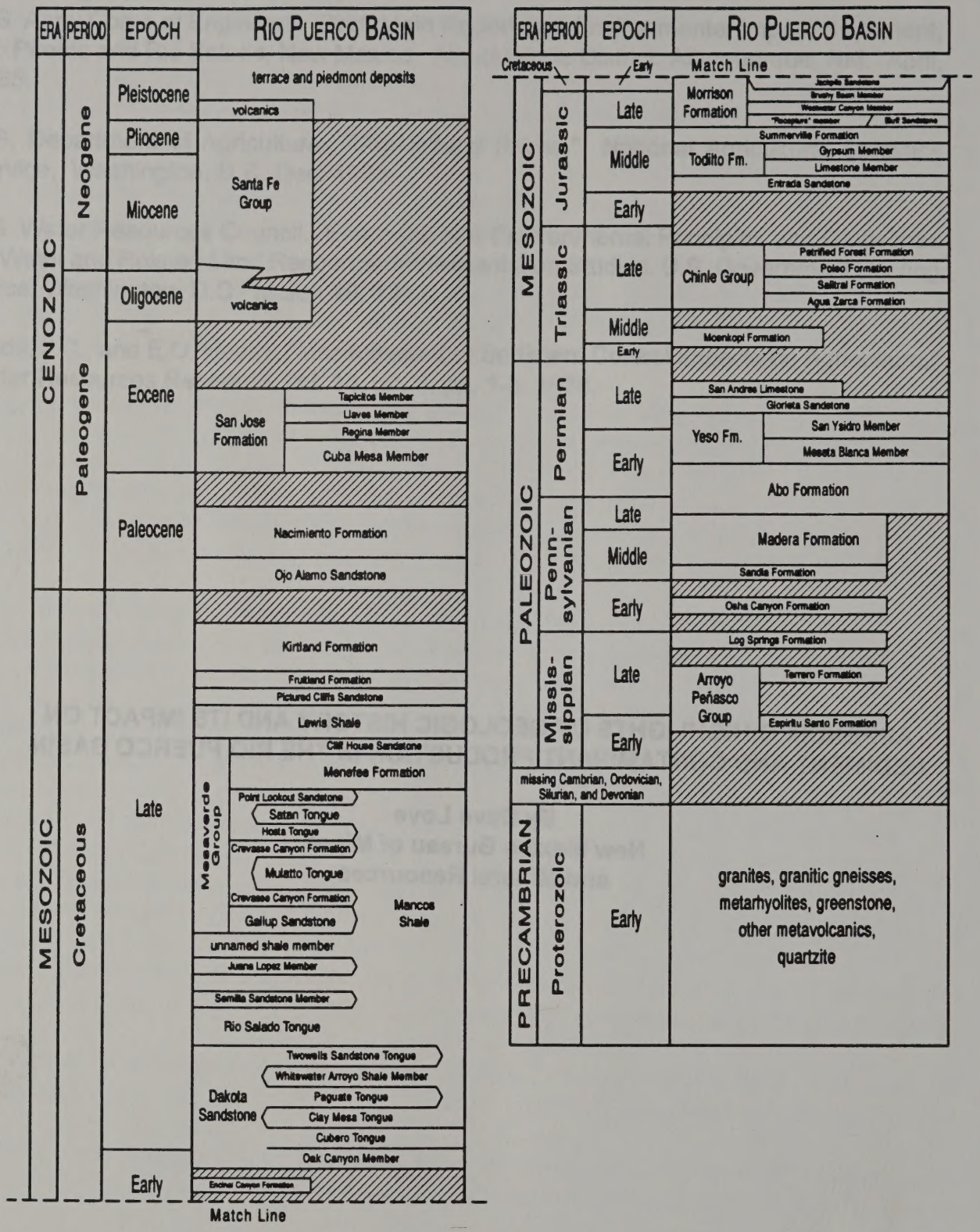

Figure C-1: Stratigraphic column of the Rio Puerco drainage basin. Time units are on the left; formations and general rock types on the right.

As a large erosional landform, most of the Rio Puerco drainage basin developed within the past 5 million years (Ma), but the rocks in the drainage basin reveal a much longer and complex geologic history. The following brief review highlights only rocks remaining from major episodes responsible for the development of the Rio Puerco, its present sediments, and contaminants. The major geologic time divisions important to the Rio Puerco are the Precambrian (Proterozoic Eon), Mid Paleozoic, Late Paleozoic, all of the Mesozoic, and major portions of the Cenozoic eras (see stratigraphic chart). The rocks have undergone several episodes of uplift and erosion, downwarping and burial, as well as moving south and north of the equator through various climatic zones as North America developed into a separate continent [Love, 1992].

Precambrian

Precambrian rocks formed before abundant fossils in the rock record of Earth history, roughly from Earth's beginning 4,500 Ma ago until 570 Ma ago (see chart). The advent of life with preservable hard parts (shells, skeletons) marks the beginning of Cambrian period. The oldest rocks in this part of North America, including the Rio Puerco drainage basin, are seen in the uplifted cores of the mountain ranges (Nacimiento, Zuni, Ladron, Lucero), but they underlie all other rocks in the region and provide a base upon which younger rocks were deposited or injected through. They are 1,675 to 1,825 Ma old (Proterozoic) and consist of igneous and metamorphic rocks that were originally sediments and volcanic rocks on a continental margin. These rocks have been buried to 46,000 feet, heated to 900° F, intensely deformed, and pushed apart by molten igneous rocks that later cooled in place. Molten intrusions continued to be injected throughout northern New Mexico until about 1,400 Ma. All these hard, crystalline metamorphic and igneous rocks were later uplifted and eroded to form a broad, low-relief platform (platform = gently sloping margin of continents) similar to the coastal plain and continental shelf of eastern North America.

Precambrian outcrops in the Rio Puerco drainage account for only 2.4 percent of the area, but the rocks resist weathering and abrasion during transport, so many of the larger clasts moving downstream are Precambrian rocks. These clasts get recycled over and over, moving from older stream terraces and basin fill to younger channels as erosion continues. Minor ore deposits are found in the Zuni, Nacimiento and Ladron Mountains. These include fluorite-barite-galena ore, copper-lead ore, and uranium ore.

Early to Middle Paleozoic -- (Cambrian, Ordovician, Silurian, Devonian, Mississippian)

A time gap of over 1,000 Ma occurs between formation of the topographically low-relief platform and the first preserved marine deposits found in the Rio Puerco area of Early Mississippian age (see chart) roughly 330 Ma ago. In general, the region from south-central New Mexico to the Great Lakes was arched up so seas advanced and retreated

around the margins of this small landmass. Because regional preservation of sediments to the east, south and west of the former landmass is more complete, the western margin of the North American continent can be located and the position of the continent relative to the poles can be traced. The Rio Puerco area was near 10° north of the equator and drifted to near 20° south of the equator during early Paleozoic time. The seas advanced and retreated across the arch to the southwestern margin of the continent. Thus lower Paleozoic marine deposits reflect medium and high stands of the sea and consist of limestones deposited in warm, tropical seas. Cambrian deposits reach the Four Corners, but are absent in most of northwestern New Mexico. Silurian and Devonian rocks are also absent, and although Mississippian limestones extended across all of the area, they were later partially eroded away. Western North America collided with oceanic blocks and islands during mid-Paleozoic time, uplifting part of the continental margin and much of the interior and subjecting the region to further erosion.

Late Paleozoic -- (Pennsylvanian and Permian)

During Pennsylvanian time (roughly 325 million years ago), the eastern and southern margins of North America were crumpled in collisions with Europe and Africa. In the Rocky Mountain region, large mountain blocks were uplifted, and large basins subsided in between. In New Mexico and the Four Corners region, large mountain ranges and adjacent basins formed. The uplifts shed coarse granular sediments into adjacent basins, but some basins remained below sea level much of the time. Stream-deposited sediments of the Sandia Formation were deposited first, then marine mudstones and limestones of the Madera Formation were laid down. Later, these formations were removed by erosion from some uplifted areas.

During Permian time, some uplifts in Colorado and Utah continued to rise and shed coarse sediments southward into New Mexico. To the south were extensive eolian sand seas (ergs); south of them were low salt flats called sabkhas, and farther south was open ocean. Again, sea level rose and fell. The sabkhas, sand seas, and streams from the mountains transporting debris moved back and forth, so cyclic repetition of packages of sediments is common. Sabkhas and marine-margin sandstones and limestones representing this time period are commonly preserved in New Mexico (all Permian formations on stratigraphic chart).

Nothing is preserved to indicate what happened during the late Permian in this region. Western North America again collided with oceanic blocks and island arcs, uplifting the western part of the continent. The end of the Permian was disastrous for life. About ninety percent of all biological families disappeared before the beginning of the Mesozoic.

In terms of sediment and contaminant production, The Sandia and Madera formations produce minor amounts of clay. Limestone commonly breaks down during weathering and

transport, releasing Ca and CO3 ions. Silica nodules within the limestone resist weathering and may be transported great distances. Locally the Madera formation may be a host for extremely minor metal-sulfide deposits. The Abo and Yeso formations currently weather to form red sands and muds. They locally produce gypsum (CaSO4.2H20) which affects water quality. Locally there is some copper sulfide and oxide mineralization (red-bed copper deposits), but these formations are not major producers of heavy metal contaminants. The Glorieta Sandstone weathers to produce light-colored sand. Locally the San Andres Limestone plays host to minor ore deposits in the Zuni Mountains.

Mesozoic -- (Triassic, Jurassic, and Cretaceous)

The Four Corners area in Mesozoic time (65 to 245 million years ago) experienced many different kinds of depositional environments. At first, older rocks were eroded away as the north American continent was raised above sea level. During Triassic time (208-245 million years ago), drainages developed and flowed northwest from Texas, southern New Mexico, and Arizona across northern New Mexico, Arizona and Utah. Other streams joined from the remnants of Paleozoic mountains in Colorado and extreme northern New Mexico. Some of these streams formed fairly formidable channels and carried large logs, but most channels were smaller and had broad muddy floodplains. The first dinosaurs as well as many other reptiles, amphibians, and fish are found fossilized in the channel and floodplain deposits.

During Jurassic time, the climate became more desert-like as the continent passed northward through the Subtropical Belt. Large ergs (sand seas) swept across the region, with huge salinas and playa lakes occupying the lowest part of the region for millions of years at a time. Streams from the southwest flowed across the Four Corners to a playa in southwestern Colorado. Uranium became concentrated in some of these stream and playa deposits.

A continental-scale seaway stretching from the Gulf of Mexico to the Arctic developed in Cretaceous time (65 to 130 million years ago). The axis of the seaway was in eastern Colorado, but the western shoreline moved back and forth across the Four Corners area from about 90 million years ago to roughly 70 million years ago. At the same time, the continent kept subsiding, so the cycles of flooding are preserved in the region along with coastal plains advancing across former marine deposits. Deposits consist of stream, floodplain and coastal swamp deposits west of the shoreline, shoreline sands, offshore sand bars, and offshore marine muds (shales). These deposits alternate vertically too, as the depositional environments moved back and forth, each preserving the deposit beneath.

Near the end of Cretaceous time and continuing into early Cenozoic time, several major

events took place. Super continents split up, forming the major continents recognized today. The seas that had stretched north-south across middle North America retreated to the modern ocean basins. The Rocky Mountain and Cordilleran mountain chains rose and slid toward adjacent lowlands. One or more significant bodies from space (comets, asteroids?) crashed into the Earth. Incredibly large volumes of volcanic rocks poured out on the surface of the Earth on other continents (unrelated to the extraterrestrial impacts). The climate became cooler. All these events had a profound effect on life at the time.

In the Four Corners area, the seas left to the northeast, and molten rock was injected below the surface of local areas to form igneous rocks now exposed in the Carrizo, La Plata, and Elk Mountains. The Rocky Mountains and previous uplifts (Defiance Plateau, Zuni Mountains) slowly rose and the San Juan Basin and adjacent basins subsided.

Rocks of Mesozoic age have by far the most major influence on the morphology of the Rio Puerco drainage basin and account for the bulk of sediment and contaminant production. Alternating sandstones and mudstones of most of the Mesozoic formations ultimately erode to produce the sandstone cliffs rimming mesas, barren shale slopes, and valleys eroded into shale and mudstone. Major mud producers include the Chinle Group, Summerville and Morrison formations, and the Mancos, Menefee, Lewis, Fruitland, and Kirtland formations. The Cretaceous shales break down into smectitic (shrink-swell) clays and silts. The Morrison and Todilto units are the primary hosts for uranium deposits in the Grants uranium belt. Minor copper sulfides and oxides occur in rocks of the Chinle Group, while Cretaceous coals yield minor quantities of several heavy metals. The Todilto Formation and Cretaceous mudrocks produce large quantities of soluble sulfates.

Cenozoic -- (Early, Middle and Late)

During the early Cenozoic Era (roughly 50 to 65 Ma ago) northwestern New Mexico experienced the continued rise of the Rocky Mountains and other uplifts on the Colorado Plateau along with subsidence of structural basins. Sediments eroded from the mountains were deposited in the adjacent basins and were preserved as the basins continued to sag. Volcanoes continued to erupt ash and other volcanic debris which was eroded and deposited in the basins. The San Juan basin is the largest of these early Cenozoic structural basins. The shape and size of the upper Rio Puerco drainage is partially determined by the formation of the structural basin and by the sedimentary rocks currently exposed there.

In "mid" Cenozoic time (between 50 and 20 million years ago) very little of the geologic record is preserved in the Four Corners area or in the Rio Puerco drainage. The Colorado Plateau experienced uplift and erosion. Topographic relief of the adjacent mountains was subdued to nonexistent. Subvolcanic rocks were injected into the older sediments of the Plateau beginning about 40 million years ago and continue to be emplaced in minor

amounts to near historic time. River and eolian deposits are preserved beneath 30 million-year-old lavas in the Chuska Mountains. Shiprock and a number of other subvolcanic plumbing systems indicate where other volcanoes were about 30 million years ago as well. To the north, east, and south, major volcanic piles developed and shed sediments to the south, west, and north. Few of these sediments are preserved in the Rio Puerco drainage basin. The Rio Grande rift began to form roughly 30 Ma ago and received sediments from the slightly higher Plateau and adjacent Rocky Mountains. It is likely that the Rio Puerco drainage basin began to develop adjacent to the Albuquerque rift basin as it began to sag.

Beginning about 15 million years ago (late Cenozoic time), the Colorado Plateau, along with the surrounding provinces (Basin and Range, Rocky Mountains) began to be uplifted again very gradually; several thousand feet of uplift has occurred. Modern drainages began to develop and incise. Much of the modern landscape developed under continuing processes of erosion. As the region has risen, orographic effects of surrounding mountains and plateau edges have denied moisture to the Four Corners area, making it progressively drier. Moisture in the mountains has maintained river flow through this arid region. Stream terraces along the major rivers reflect cycles of increased runoff and decreased runoff during glacial and interglacial episodes in the high mountains.

Along the southern edge of the Colorado Plateau, several large volcanic fields have developed in late Cenozoic time. Large volcanoes such as Mount Taylor and Jemez Mountains erupted large amounts of ash and lava. Subsidiary volcanic fields along the Rio Puerco eroded to leave behind plumbing systems called volcanic necks or plugs. Later more fluid eruptions of basaltic lava flowed down former stream valleys in the Zuni-Acoma subprovince. Early inhabitants of these areas undoubtedly witnessed the latest of these eruptions roughly 3,000 years ago.

Development of the Rio Puerco Drainage

Subsidence of the Albuquerque structural basin and adjacent basins of the Rio Grande rift began 30 to 35 Ma. The initial Albuquerque basin was broad and shallow, with volcanic piles to the northeast and southwest. It is possible that the early basin was actually two separate smaller basins aligned north-south. Although most evidence is now buried within the basin, streams from all sides of the basin probably flowed into it, ponded in the lowest parts, and evaporated. Deposits presently exposed along the northern Ceja del Rio Puerco west of Rio Rancho provide evidence of eolian sand dune fields, mud flats, and permanent-to-ephemeral lakes (playas) in the past. Overlying these deposits are the first indications of an early Rio Puerco drainage coming into the basin from the northwest. Playa deposits are also exposed in badlands west of the lower Rio Puerco. These are overlain by ancestral Rio Puerco-Rio San Jose gravelly sands.

As the Albuquerque basin(s) continued to subside, erosion of the surrounding highlands

almost kept pace, but the headwater areas of the Rio Puerco apparently were higher plateaus with low topographic relief. Remnants of lava flows from volcanic eruptions roughly 8 Ma ago preserve small linear stream valleys on the crest of the Lucero uplift. The Mount Taylor-Mesa Chivato volcanic field began to erupt roughly 4 Ma ago and continued to produce basaltic lavas for over 1 million years. These lavas covered a relatively low-relief surface currently preserved beneath Mesa Chivato. Younger vents and flows are at lesser elevations along both the Rio Puerco and Rio San Jose. The bulk of erosion in both the Rio San Jose and middle Rio Puerco took place between 2.6 and 0.3 Ma ago. The valleys were incised as much as 3,000 feet below the Mesa Chivato surface and over 516 mi^3 of sediment were removed from the upper Rio Puerco and Rio San Jose drainage basins. Much of this sediment helped aggrade the western two-thirds of the Albuquerque basin.

The Rio Grande entered the Albuquerque basin from the northeast roughly 4.5 Ma ago and integrated rift basins south to the Las Cruces area. The Rio Puerco system joined the Rio Grande and both streams continued to aggrade in the Albuquerque basin until roughly 0.5 to 1 Ma ago. The Rio Grande then began to incise its valley through former basin-fill deposits and the Rio Puerco and Rio San Jose followed suit. The southerly course of the lower Rio Puerco appears to have been influenced by active faulting along north-south faults.

Incision along all three streams (and their tributaries) has been episodic. Several terrace levels have been described along the streams, but most terraces are not well preserved along the Rio Puerco and Rio San Jose. The older terraces predate lava flows 0.32 and 0.38 Ma old.

Sometime prior to the late Pleistocene, roughly 18 thousand years ago (ka), the Rio Grande and Rio Puerco incised to their maximum level. The Rio Grande was as much as 90 feet lower than it is today. Valley fill in the lower Rio Puerco is as much as 140 ft thick. Both streams have aggraded because more sediment reached their valleys than they can transport under current climatic conditions. Valley fill in the Rio Puerco is estimated to be roughly 1.4 mi^3.

The upper 10-14 m of valley fill in the Rio Puerco shows paleochannel systems of both arroyo and non-arroyo channels. At least three paleo-arroyos have been described along the lower Rio Puerco, one dated roughly 2.5 ka and one dated roughly AD 1300-1400.

The modern arroyo in the Rio Puerco valley exhibits a complex geomorphic history which has not been reconciled with historic accounts of channel widths and depths, land and stream use, and arroyo entrenchment. The upper and lower Rio Puerco show inset terraces which indicate that an arroyo cut and partially filled in before the present arroyo cut. However, the middle Rio Puerco apparently lacks this episode along its present course. The Albuquerque 15 minute quadrangle, mapped in 1888 and published in 1893,

shows the Rio Puerco west of Albuquerque as a relatively small channel on the east side of the valley near the base of Mesita Negra. Aerial photographs of 1934 show Rio Puerco arroyo deeply incised on the west side of the valley with a much larger meander wavelength than the older channel. A similar former channel complete with dead cottonwood trees is reported south of Hidden Mountain along the east side of the Puerco valley.

The 1934-5 aerial photographs show that not all of the Rio Puerco was deeply incised even then. Downstream from Cabezon, the Rio Puerco was shallow, probably due to the channel being "hung up" on a sandstone ledge. Even major tributaries were not incised or incompletely incised in the 1930's. Other reaches of the Rio Puerco apparently were shallow enough to dam and divert water to irrigation systems. These dams were no longer operational by the early 1950's.

During the twentieth century much of the Rio Puerco has widened and an inner channel-inner floodplain has developed, replacing the formerly braided channel that flooded from arroyo wall to wall. The braided channel still exists in one reach of the upper Rio Puerco, and apparently it is aggrading rapidly along this unstudied reach. Tamarisk was purposefully planted along the Rio Puerco in three areas in the 1920's [Bryan and Post, 1927] and has colonized much of the floodplain and channel margins. Willows and a few cottonwoods also grow along the channel margins.

REFERENCES

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APPENDIX D: HISTORICAL PERSPECTIVE

The Rio Puerco drainage has a long history of human habitation, dating back at least 1,500 years. From approximately 400-700 AD, Basketmaker III Indians were planting in irrigated plots along the Rio Puerco. For the next eight centuries the area would be occupied by a series of pueblo cultures that would peak, then decline. There are many archaeological sites throughout the drainage, the most outstanding being Pottery Mound. This is a large Pueblo IV inhabitation with numerous kivas and mural frescoes. It appears that all of the pueblos along the Rio Puerco were abandoned by the time of the Spanish Entrada.

Spanish influence in the Rio Puerco area was minor until the middle of the 18th Century. At this time the colonial government began awarding land grants to encourage settlement and to reward service. These grants included the Montoya Grant (1766, 2,967 acres), the Ignacio Chavez Grant (1768, 46,358 acres), the San Ysidro Grant (1786, 11,476 acres), and the Ojo del Espiritu Santo Grant (1815, 113,141 acres). Sometime during this period the village of Guadalupe was established on the east side of the Ignacio Chavez Grant. Navajo and Apache depredations were a constant threat, but by the late 1700's Spanish settlements along Rio Puerco were grazing thousands of sheep in the area, and families were moving into the Rio Puerco valley from Albuquerque. Many of these new settlements were destroyed within thirty years by Indian raiders.

In 1821 Mexico won its independence from Spain. Military presence in New Mexico decreased and Indian raids increased. The next two decades were marked by continuous bloodshed between the Navajos and Hispanics, and the settlers of the Rio Puerco either fled or were killed.

Mexican independence also led to the softening of the former Spanish Colonial policy of exclusion of outside trade. The Santa Fe Trail was opened, traders from the east established their presence, and it was only a matter of time that the policy of Manifest Destiny would put New Mexico in the hands of the United States. The treaty of Guadelupe Hidalgo conveyed New Mexico to the United States in 1848.

A chronology of some important events in the history of the Rio Puerco since the beginning of the Territorial Period is presented in the following summary.

1846: Colonel Stephen Doniphan conducts a campaign to bring the Navajos to terms. Both parties sign a meaningless treaty. Accompanying the expedition is Lieutenant James Abert, whose report on the area to Congress is the first official American document concerning the Rio Puerco. He mentions 30-foot vertical banks on the Rio Puerco near Poblazon.

1848: The Treaty of Guadelupe Hidalgo conveys New Mexico to the United States.

1850: Lieutenant Colonel John Washington conducts a punitive campaign against the Navajo. Lieutenant James Simpson issues the report, which contains the first official accounts of Inscription Rock and the ruins of Chaco Canyon. Also included are

descriptions of the Rio Puerco area. He mentions that where the army crossed the Puerco several miles upstream from Cabezon, there were stream banks between 20 and 30 feet high that had to be graded down to permit the passage of artillery and pack animals.

Jose Perea moves to Bernalillo with 1,000 to 1,200 sheep and begins running them on the Ojo del Espiritu Santo Grant. Hispanic farmers found the community of Cabezon.

1853: Jose Perea's herd has grown to 50,000 sheep that pasture in the Ojo del Espiritu Grant during the winter.

1864: The Navajos are defeated at Armijo Lake. About this time, small farmers begin to move into the Rio Puerco area and new settlements are established. These farmers construct diversion irrigation systems.

1868: A treaty establishes the Navajo Indian Reservation in Arizona and New Mexico.

1870: Most of the upper Rio Puerco is controlled by two cousins, Mariano Otero and Mariano Perea. Otero runs 90,000 sheep and 9,000 cattle while Perea runs 150,000 sheep. Many local farmers engage in livestock production on a "partido" (share) basis with Otero and Perea.

1871: The post office opens at Cabezon, which is now a flourishing trade center. The Star mail, freight and passenger service runs though Cabezon on the way from Santa Fe to Fort Wingate. Service continues until 1912.

1887: The post office is established in Cuba. The name of the community is changed from Nacimiento.

1888: Los Cerros is abandoned. Los Cerros is 34 miles upstream from the confluence of the Rio Puerco and Rio Grande. In the following years the abandonment of settlements will progress upstream.

1889: The Rio Puerco Irrigation and Improvement Company is organized by Charles Lewis, Marciano Otero, T. B. Catron, Jesse Anthony, and Harvey Wells. The company begins buying property and water rights along the Puerco. Their plan is to build a canal 120 miles long on the east side of the Puerco. The canal is to stretch from the mountain headwaters to a dam to be built on the Montano Grant.

1890: Cabezon continues as a trading center, with three stores and seven saloons.

1896: San Ignacio (river mile 62) and San Francisco (river mile 73) are abandoned by this year. The Old English dam, built by the Rio Puerco Irrigation and Improvement Company, washes out.

1900: Cuba is a wheat and corn center, with production from lands along Leche and Nacimiento Creeks. This part of the Rio Puerco basin is known as "the bread basket of New Mexico."

1910's: There is a peak in livestock grazing. Oats are exported from the area during World War I.

1922: The dam on the Rio Puerco at Cabezon is washed out.

1925: Irrigated acreage between Casa Salazar to Cuba has declined from 10,000 acres in 1880 to 3,000 acres by 1925

Late 1920's: Casa Salazar is abandoned

1930's: There is a brief increase in sheep raising. La Ventana is prospering due to coal mining.

1936: The Soil Conservation Service rebuilds the dam at San Luis.

1951: A flood destroys the dam above the village of San Luis that had been constructed by the SCS in 1936. The dam will not be reconstructed and its loss leaves the villages of San Luis and Cabezon without water for irrigation.

1959: Widdison's history of the Rio Puerco area states that the decline in the settlements and the lessening in the intensity of land use "may be viewed as a compensation for the overuse of the land that preceded it."

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APPENDIX E: SUMMARY OF PREVIOUS FEDERAL AGENCY ACTIVITIES

Of the 3.9 million acres in the drainage area, over one million acres are administered by the Bureau of Land Management, 850,000 acres by the U. S. Forest Service, and 400,000 acres by the Bureau of Indian Affairs.

What follows is a synopsis of important government activities pertaining to the Rio Puerco that has been compiled from numerous sources.

1854: The office of U. S. Surveyor General in New Mexico is created. This office is to be responsible for recognizing Mexican and Spanish Land Grant claims. The Surveyor General is placed under the supervision of the General Land Office.

1926: The Middle Rio Grande Conservancy District sets out three plantations of salt cedar along the Rio Puerco. The plants are intended to check erosion.

1934: Congress passes the Taylor Grazing Act. It is intended to halt overgrazing on public rangeland, but it does not. Political pressure from the grazing industry effectively hamstrings the implementation of the Taylor Grazing Act [Sheridan, 1981]

The same year the purchase of submarginal land begins under New Deal rural rehabilitation programs. The federal government acquires the Ojo del Espiritu Santo Land Grant, which had come into the possession of Thomas Catron around the turn of the century. The price - $282,852 for 113,141 acres.

1935: Indian Service purchases portions of the Ojo del Espiritu Santo and Montoya land grants for the Laguna, Zia, and Jemez Indians. The newly formed Soil Conservation Service is given Civilian Conservation Corps (CCC) and Works Progress Administration (WPA) labor to carry out its activities.

1936: The federal government purchases the majority of the San Ysidro Land Grant. The San Ysidro Land Company receives $12,477 for 9,982 acres.

1937: The Secretaries of Agriculture and Interior create the Interdepartmental Rio Grande Advisory Committee. Members include the Forest Service, Soil Conservation Service, Resettlement Administration, Indian Service, General Land Office, and the Grazing Service.

1938: The Secretaries of Agriculture and Interior upgrade the Interdepartmental Rio Grande Advisory Committee to the Interdepartmental Rio Grande Advisory Board. The board purchases the Antonio Sedillo Grant in exchange for a portion of the Ojo del Espiritu Santo Grant. The board also negotiates a deal between the Santa Fe Railroad, the Soil Conservation Service, and Frank Bond (a prominent rancher) to exchange all railroad lands within the Cuba-Rio Puerco LU (refers to lands that were repurchased by the Federal government from failed homesteaders) for federal lands outside the area.

1940: U. S. Government purchases the majority of the Ignacio Chavez Grant form Alfred A. Gossett and others. They receive $67,350 for 45,940 acres.

The Soil Conservation Service develops the Rio Puerco Project Plan.

1942: The Interdepartmental Rio Grande Advisory Board is abolished. The Soil Conservation Service proposes consolidating all federally-owned lands in the eastern half of the Cuba-Rio Puerco LU project under its administration.

1946: The Bureau of Land Management is created from the Grazing Service and the General Land Office.

The Farm Security Administration, ordered by Congress to divest itself of Cuba-Rio Puerco LU lands, transfers them to the Forest Service.

1948: Congress authorizes the comprehensive plan jointly developed by the Bureau of Reclamation and the Army Corps of Engineers for relieving problems due to sedimentation of the Rio Grande between Velarde NM and Elephant Butte Reservoir. The Corps of Engineers is to construct and operate flood and sediment control dams on the Rio Grande, Rio Chama, and Jemez Creek. Bureau of Reclamation is to rehabilitate El Vado Reservoir, drainage and irrigation systems along the middle Rio Grande, and improve the Rio Grande channel to reduce flooding and conserve water.

1950: The Flood Control Act of 1950 further authorizes the Middle Rio Grande Project

1951: Bureau of Reclamation begins channelization above Elephant Butte Reservoir.

1953: The Forest Service and the BLM initiate the San Luis Study. This is to be a 20-year project that monitors erosion control, sediment yield, and grazing impact.

Bureau of Reclamation begins intensive aerial spraying campaign along the Rio Grande above Elephant Butte. Herbicide is intended to control salt cedar, a plant introduced in the 1920's, but also kills cottonwoods and willows.

1954: At the request of the Department of Interior, the BLM receives administration of the Cuba-Rio Puerco LU lands. BLM begins construction of detention dams and instigates watershed tillage practices such as ripping, pitting, and furrowing.

1955: Studies by the Bureau of Reclamation and Corps of Engineers document aggradation of the channel and floodplain of the Rio Grande.

1960: Forest Service begins evaluating the effects of the land treatment practices on

the range. Various equipment such as the Calkins pitter, the Jayhawk ripper, and the Marden brush cutter are tested.

1962: The BLM targets the Rio Puerco as a priority area for its "frail lands" program aimed at stopping erosion. Estimated cost - $1,116,300 for livestock water development, fencelines, detention dams, soil treatments such as ripping, pitting, and furrowing, and vegetation control such as brush removal, seeding, and herbicide spraying,

1963: A document prepared by the BLM states that "the Rio Puerco watershed is probably more seriously deteriorated than any other formerly productive land in the nation." This report outlines strategies for the Rio Puerco Project, and raises the cost estimate to $16.2 million for the period 1963-1969. Report addresses land treatments, vegetation manipulation, and detention structures, but cautions that "range improvement efforts without intensive grazing administration in the area would accomplish nothing more than a brief upsurge in productivity and a momentary lapse in sedimentation." The report lowers estimates of carrying capacity from 9-11 animal units to 4-6 animal units.

1964: Forest Service publishes data from the San Luis Experimental Study. This study attempts to establish the relationship among precipitation, vegetation, grazing practices, surface runoff and sediment production. A 1972 document by the BLM states that "In many facets of watershed and range management [in the Puerco area], this study is the only quantitative source of data."

1965: Jemez and Zia Pueblos recieve 81,656 acres of the former Ojo del Espiritu Land Grant from the BLM.

1966: USGS publishes Cornfield Wash study which concerns the effect of land treatment practices.

Late 1960's: New Mexico State Highway Department reroutes the Rio Puerco below Cuba in order to straighten Highway 44 and to avoid building two bridges. However, the straightened river accelerates erosion and within 25 years the channel is impinging on the roadbed.

1968: The BLM constructs its last detention dam in the area. During the 1950's and 1960's the BLM constructed approximately 650 erosion control structures in the Puerco drainage. Emphasis is shifted to grazing allotment management plans (AMPs).

1972: The Rio Puerco Special Project is evaluated. BLM decides to shift emphasis from watershed stabilization practices to grazing management facilitating projects. Priority is given to develop grazing allotment management plans (AMPs). The report recommends

that contour ripping and furrowing should be avoided except when necessary, and that off-road vehicle use be kept to a minimum.

Corps of Engineers completes survey for flood control and allied purposes along the Rio Puerco and Rio Salado. The study considers benefits from constructing a 440,000 acre foot capacity dam near Hidden Mountain.

1973: Congress passes the Endangered Species Act (PL 93-205)

1974: The BLM Rio Puerco Watershed Management Plan is approved. This plan calls for the development of ten water pipelines for grazing purposes. Most of these were completed, though the watershed plan was never fully implemented.

The National Resource Defense Council files a lawsuit against BLM alleging that the ranges are in a deteriorating condition, livestock trespass is out of control, livestock numbers exceed grazing capacity, and proper forage has not been allocated for wildlife. In the settlement, BLM agrees to prepare 14 Environmental Impact Statements in New Mexico, the first being in the Rio Puerco drainage.

1975: BLM conducts a soil and forage resource inventory in the Rio Puerco drainage.

1976: The Federal Land Policy and Management Act (PL 94-579) makes the BLM responsible for the long-term productivity of lands under its supervision.

1978: In the Public Rangelands Improvement Act (PL 95-514), Congress recognizes that public rangelands are producing below their potential and that rangeland conditions will remain the same or decline under present levels of funding [Sheridan, 1981]. Under this law, Congress commits $365 million over 20 years for a program of "intensive public rangelands maintenance, management, and improvement". However, this money is subject to annual appropriations.

Secretary of the Interior James Watt, on behalf of 34 Rio Puerco grazing permittees, files a suit [Valdez, et al. vs. Applegate, et al.] intended to prevent the BLM from implementing AMPs or actions proposed in Environmental Impact Statements. In New Mexico the BLM grazing fee is $1.51 per AUM, compared to private land grazing fees which run $5.20 per AUM

A letter from the Army Chief of Engineers to the Secretary of the Army recommends building the dam at Hidden Mountain.

1979: BLM and the Forest Service enter into a cooperative agreement to conduct a ten-year plan that would compare grazing management systems and resource response.

1980: The Corps of Engineers completes a feasibility study for watershed treatment along the Rio Puerco and Rio Salado. Corps recommends a program of grazing management, gully stabilization, and vegetation manipulation.

1981: Valdez, et al. vs. Applegate, et al. is settled out of court.

1982: BLM changes policy concerning range improvements and the distribution of Range Betterment Funds. By 1984 grazing permittees will be responsible for the maintenance of the 200+ miles of livestock water pipelines. Range Betterment Funds are to be drastically reduced.

1985: The Corps of Engineers recommends building a continuous flood control levee along the Rio Grande from San Acacia to Elephant Butte Reservoir, rather than dams at on the Rio Puerco and Rio Salado. Cost and the inability of the Sevilleta National Wildlife Refuge to accomodate the Rio Salado Dam are the principal reasons favoring levees for flood control in the Rio Grande valley.

1986: BLM's Rio Puerco Resource Management Plan designates 22 Special Management Areas (SMAs), including ten Areas of Critical Environmental Concern, three Research Natural Areas, one National Historic Landmark, and one National Trail.

1987: Congress establishes the El Malpais National Conservation Area (262,000 acres under BLM administration) and the El Malpais National Monument (114,000 acres administered by the National Park Service)

1989: The Texas Rio Grande Compact Commissioner writes to the Army Corps of Engineers, wanting to know why the dams along the Rio Puerco and Rio Salado were not built. He requests that the Corps include these hypothetical dams in their computer model.

1990: BLM and State of New Mexico develop pollution control plan to implement Best Management Practices (BMPs) as part of the Clean Water Act. Rio Puerco is considered a high priority.

1991: BLM issues its General Management Plan for the El Malpais National Conservation Area.

1992: Interagency group, led by BLM, begins meeting informally to coordinate activities and planning in the Rio Puerco Basin.

1993: Soil Conservation Service completes detailed soil survey of parts of Cibola, McKinley, and Valencia Counties. Study area includes a large portion of the Rio Puerco drainage.

1993: Bureau of Reclamation begins study to reevaluate sediment control projects in the Rio Puerco Basin under its General Investigations Program.

1994: S.B. 1919 is submitted to Congress. This bill would formalize interagency activities and coordination in the Rio Puerco Basin.

Model Description

A simple reservoir operation model was developed to project the effects on the water supply downstream from Elephant Butte Reservoir due to sediment deposition. This model is intended to forecast the approximate magnitudes of reservoir spills and shortages so that the effect of different rates of sedimentation can be compared and illustrated. A minimum of effort has been devoted to refinement and calibration of the model. The model was set up on a LOTUS 1-2-3 spreadsheet that automatically computes reservoir contents on a monthly time step unless a spill or shortage condition is simulated. In those events input is required via macro instructions to operate the model reservoir.

The model computes end-of-month reservoir contents (EOM contents) for each month by adding inflow to, and subtracting releases and evaporation from the previous EOM contents. No accounting for precipitation is performed. Average annual precipitation at the reservoir site is only about 8 inches and is highly variable. The effect of precipitation on reservoir contents is small in comparison to inflow, releases, and evaporation.

Evaporation is computed by determining a reservoir surface area based on the previous EOM contents and multiplying by a monthly value for reservoir evaporation. The model uses a second degree polynomial function relating EOM contents to surface area. This function was determined by a standard regression method using the 1988 reservoir sedimentation survey data. By comparison to earlier surveys the function derived from the 1988 surveys is taken to adequately represent a general relationship between contents and area. For a given storage volume, the surface area of the reservoir changed less than ten percent during 74 years of operation between 1915 and 1988. Figure F-1 illustrates the capacity-area relationship for the 1915, 1947, and 1988 reservoir surveys. The function relating area to EOM contents used in the model is:

$$A=555+[0.024(x)]-[3.3EE\text{-}9(x^2)]$$

Where, A is the reservoir surface area in acres, and x is EOM contents in acre feet.

Monthly reservoir evaporation in feet was determined on the basis of averagemonthly reservoir evaporation. Values vary by month and are higher in summer than in winter.

Monthly average evaporation values used in this analysis are:

January:	0.16	feet
February:	0.26	
March:	0.49	
April:	0.67	
May:	0.85	
June:	0.94	
July:	0.82	
August:	0.64	
September:	0.54	
October:	0.41	
November:	0.27	
December:	0.15	
Annual Total:	6.20	

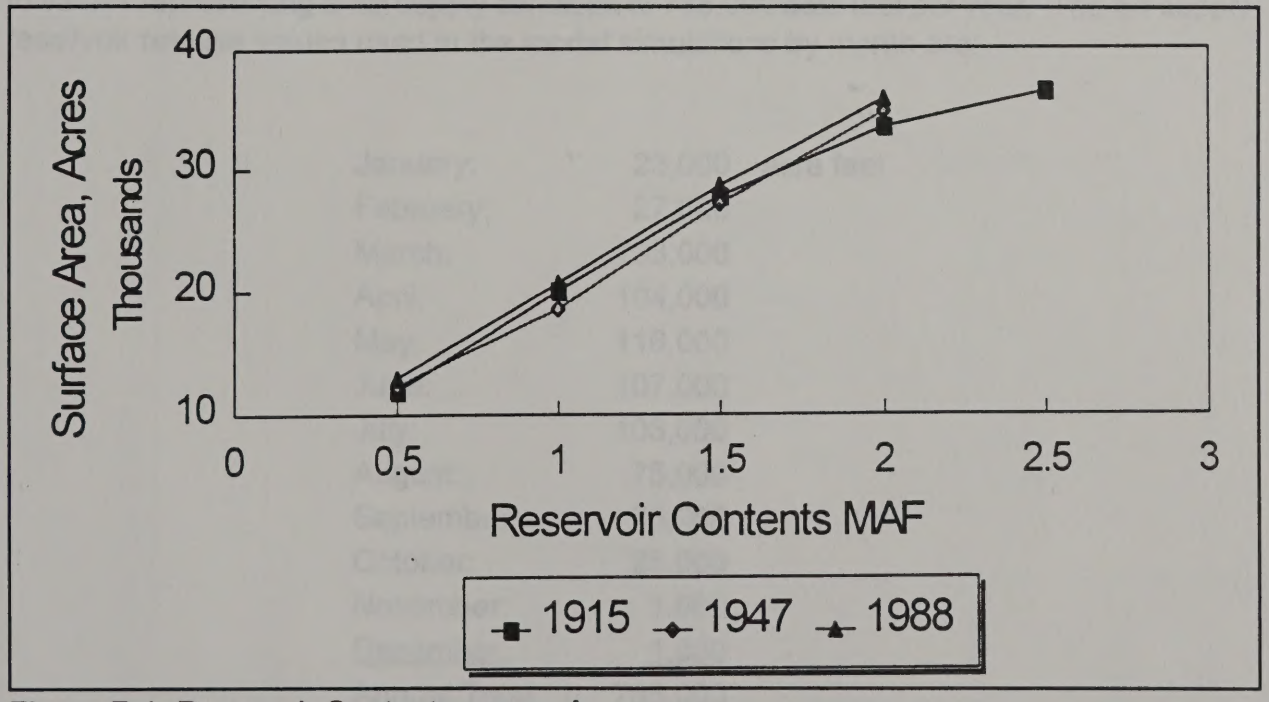

Figure F-1: Reservoir Contents versus Area

Model Verification

The model was first run using historic inflow and release data to determine how well the model simulates reservoir contents compared to the actual recorded contents. The flow of the Rio Grande at San Marcial (combined flow of the Rio Grande Floodway and Conveyance Channel) was assumed to represent reservoir inflow.

Figure F-2 compares the actual and computed values for a 74 year period from January 1917 through December 1990. The error of the computed value is also plotted. Errors in the earlier period of reservoir operation tend to be particularly high, possibly because of water going into bank storage. Attempts to determine a functional relationship between the error and model variables were not successful. For the period between 1940 and 1990, fifty percent of computed EOM contents values are within +/- 100,000 acre feet. Maximum error is 304,000 acre feet and the minimum is -132,500 acre feet. This accuracy is sufficient to simulate reservoir operations for the intended purpose. The tendency for computed values to exceed actual values when the reservoir is high and to be less than actual values when the reservoir is low mean that the model overestimates both spills and shortages and is a conservative representation of the reservoir's operation for the purpose of this analysis.

Forecasting Simulations

Four simulations were run to forecast the rough magnitude of spills and shortages that might occur in the future. Two reservoir inflow scenarios are represented. One is a 74 year simulation using the historical reservoir inflow from 1917 through 1990, and the other is a 100 year simulation of a "worst case" scenario in which three severe droughts, like that of the 1950's, occur in the next century. In this scenario, the inflow record of 1930 to 1964 is repeated 3 times. The period 1930 through 1964 includes high water years in 1941 and 1942 sufficient to fill the reservoir followed by the severe and prolonged drought of the 1950's. The effects of two rates of sedimentation are evaluated in these simulations. For each of the reservoir inflow scenarios, the maximum probable sedimentation rate for the next 100 years is projected to be 5,000 acre feet per year with no sediment control project on the Rio Puerco. A sedimentation rate of 2,000 acre feet per year represents projected conditions with a project. All simulations begin with an initial reservoir content of 1,500,000 acre feet. Maximum reservoir capacity at the beginning of each run is 2,000,000 acre feet.

Normal reservoir releases were determined by rounding and adjusting monthly averages to values representing a full supply condition of 785,000 acre feet per year. The full supply reservoir release values used in the model simulations by month are:

January:	23,000	acre feet
February:	27,000	
March:	133,000	
April:	104,000	
May:	116,000	
June:	107,000	
July:	103,000	
August:	75,000	
September:	70,000	
October:	25,000	
November:	1,000	
December:	1,000	
Annual Total:	785,000	

The model requires operator input when spills or shortages are simulated. Simulated spills occur when computed EOM contents exceed reservoir capacity. The model provides for

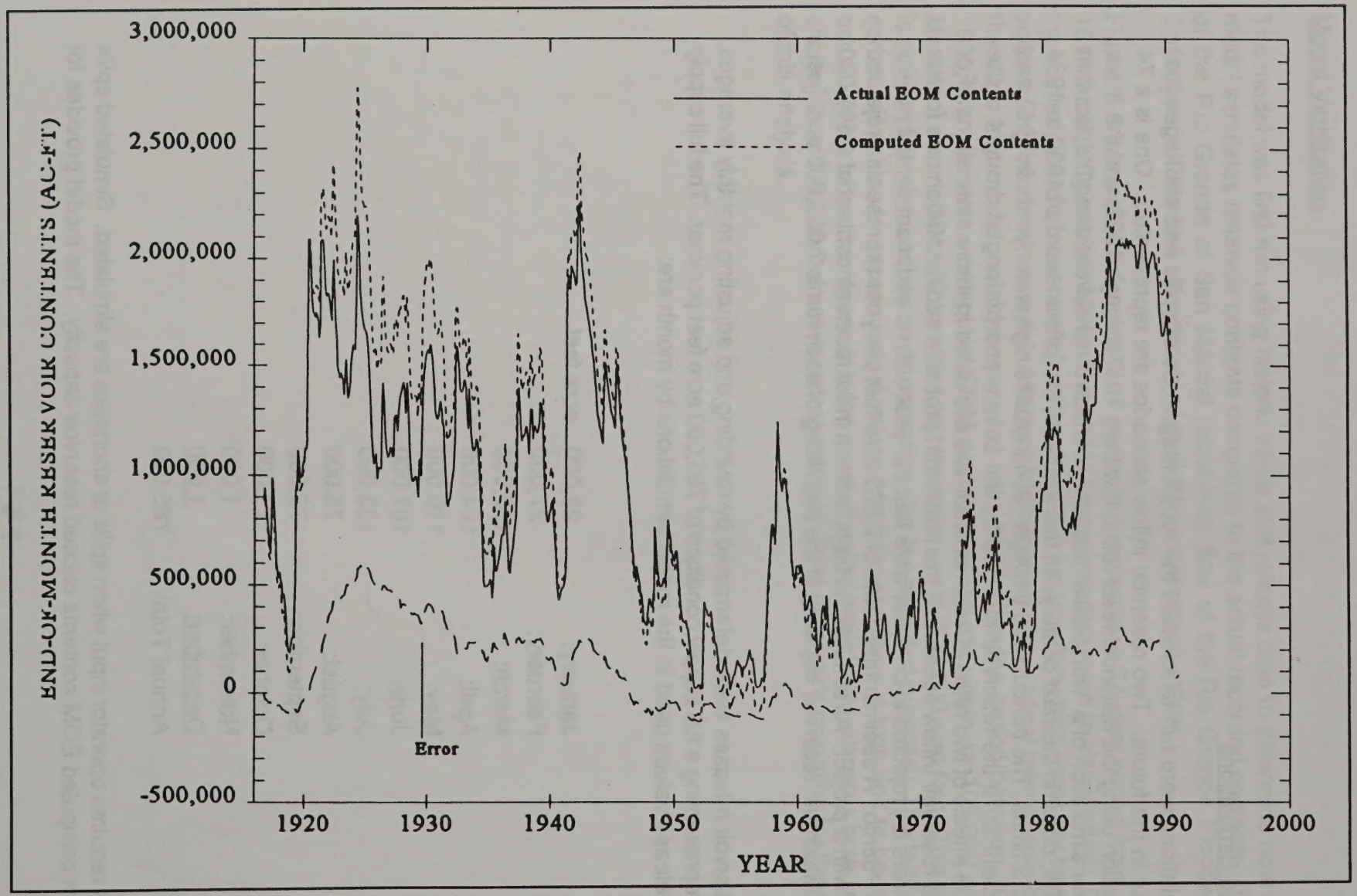

Figure F-2: Computed and Actual EOM Contents

reduction of storage capacity by computing a new maximum reservoir capacity monthly according to an annual average sedimentation value supplied at the beginning of the simulation. When a spill condition exists the model requires the operator to compute the quantity of water spilled and to set the EOM contents equal to the maximum reservoir capacity. This sequence is accomplished by a macro command. When EOM reservoir contents is computed to be less than zero, a shortage exists and releases are computed to be equal to inflow less evaporation. Shortage for the month is computed by subtracting the computed release from the normal monthly value and EOM contents is set to zero. A macro command is also used for this purpose.

Simulated reservoir EOM content plots are shown for the four simulation runs in figures F-3 through F-6. A tabulated summary of spills and shortages is given in Table F-1.

Table F-1: Summary of Reservoir Operation Simulations

74 Year Simulation Using Historic Inflow (1917-1990)			
	Annual Sediment Deposition 5,000 Acre Feet	Annual Sediment Deposition 2,000 Acre Feet	Difference due to Reduction of Sedimentation
Total Spills in 74 Years (Acre Feet)	5,845,562	5,482,442	363,120
Total Shortages in 74 Years (Acre Feet)	6,904,362	6,873,667	30,695
Total Evaporation in 74 Years (Acre Feet)	7,505,946	7,673,232	-167,286
100 Year "Worst Case Scenario" Simulation			
	Annual Sediment Deposition 5,000 Acre Feet	Annual Sediment Deposition 2,000 Acre Feet	Difference due to Reduction of Sedimentation
Total Spills in 100 Years (Acre Feet)	4,916,392	4,473,400	442,992
Total Shortages in 100 Years (Acre Feet)	12,010,569	11,788,076	222,493
Total Evaporation in 100 Years (Acre Feet)	7,251,874	7,472,374	-220,500

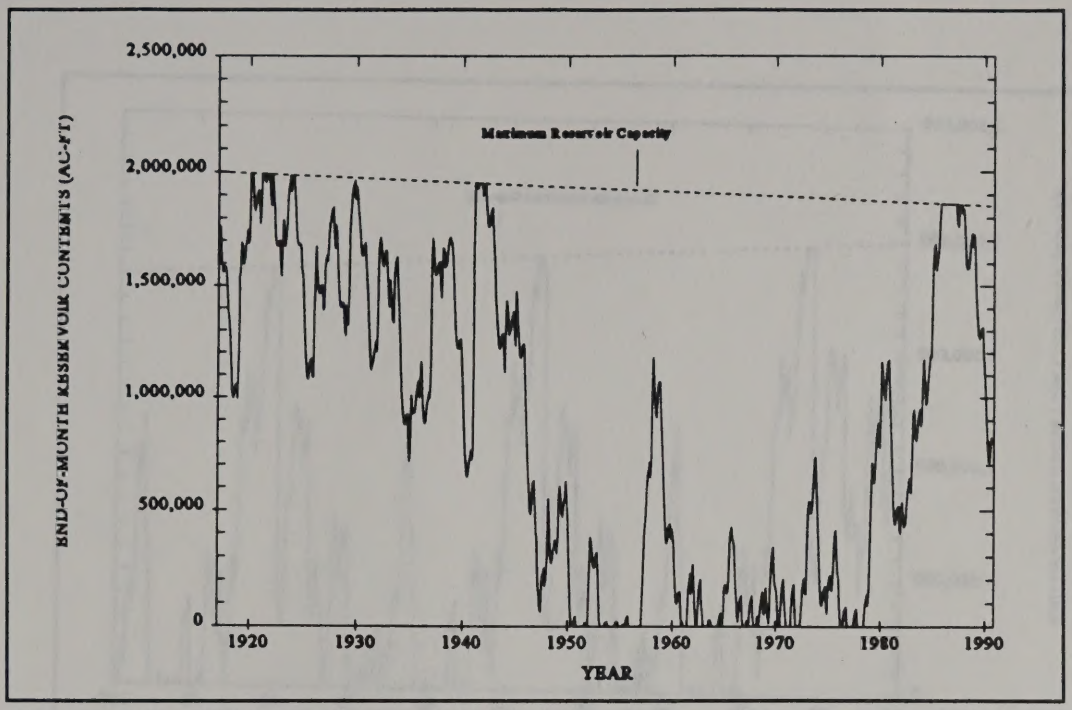

Figure F-3: EOM Contents, 74 Year Simulation, 2000 Acre Feet Annual Sedimentation.

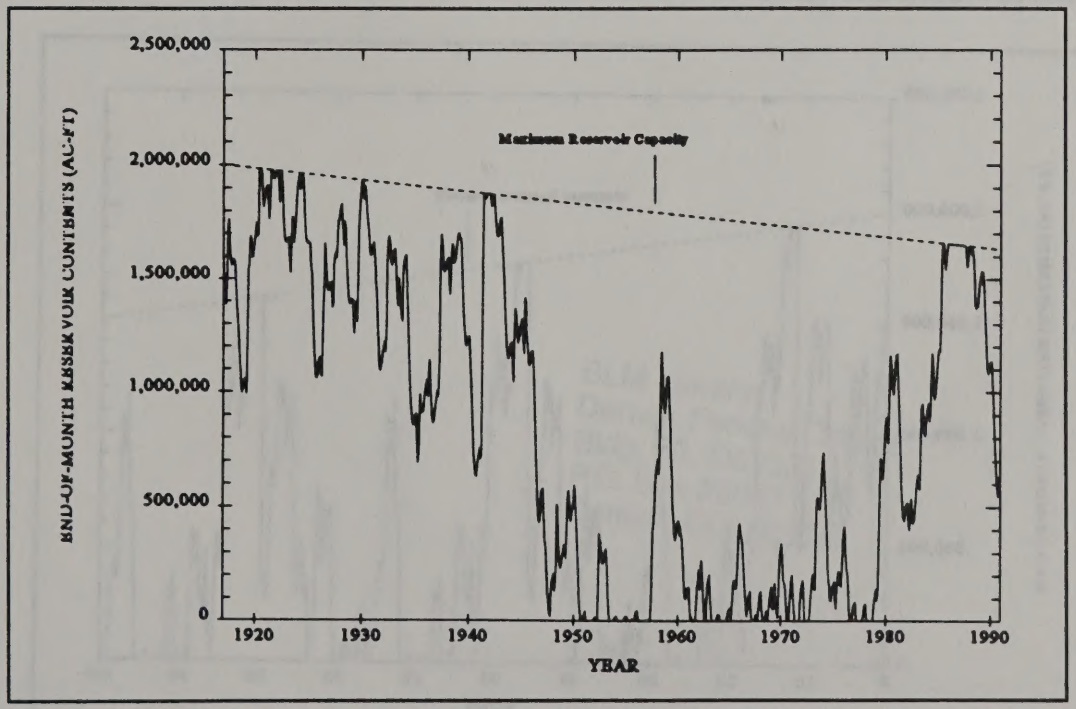

Figure F-4: EOM Contents, 74 Year Simulation, 5,000 Acre Feet Annual Sedimentation

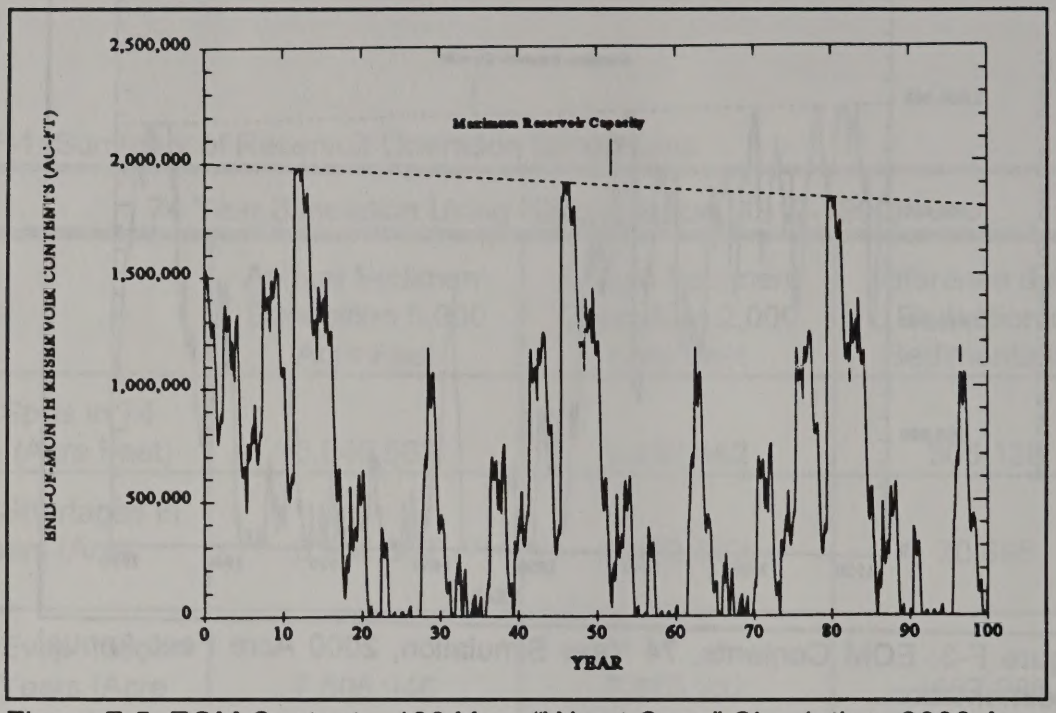

Figure F-5: EOM Contents, 100 Year "Worst Case" Simulation, 2000 Acre Feet Annual Sedimentation.

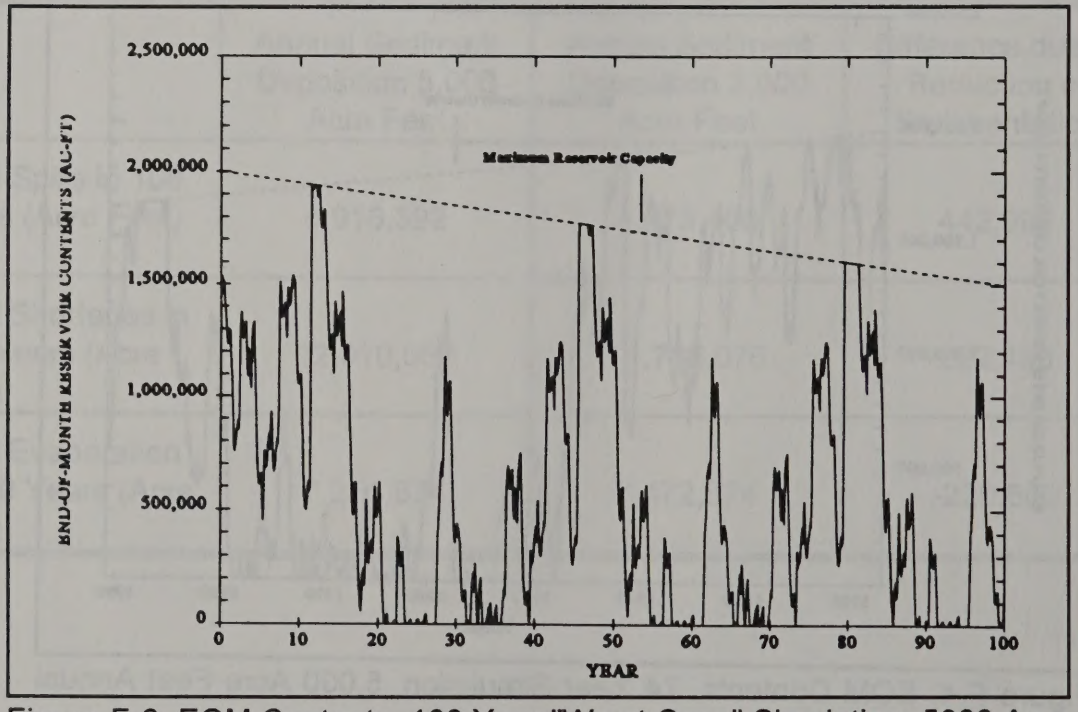

Figure F-6: EOM Contents, 100 Year "Worst Case" Simulation, 5000 Acre Feet Annual Sedimentation

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